

# Determination of Neutrino Mass Hierarchy from T2K and NOvA: Neutrino Running ONLY

Stephen Parke - Fermilab  
with Olga Mena and Hiroshi Nunokawa  
hep-ph/0609011

many discussions with Hisakazu Minakata  
HM, NN & SP: Phys. Rev. D68, 013010 (2003)

# Outline:

- Introduction  $P(\nu_\mu \rightarrow \nu_e)$
- T2K and NOvA
- LBL: Ways to determine Neutrino Mass Hierarchy
- Further out ways
- Conclusions

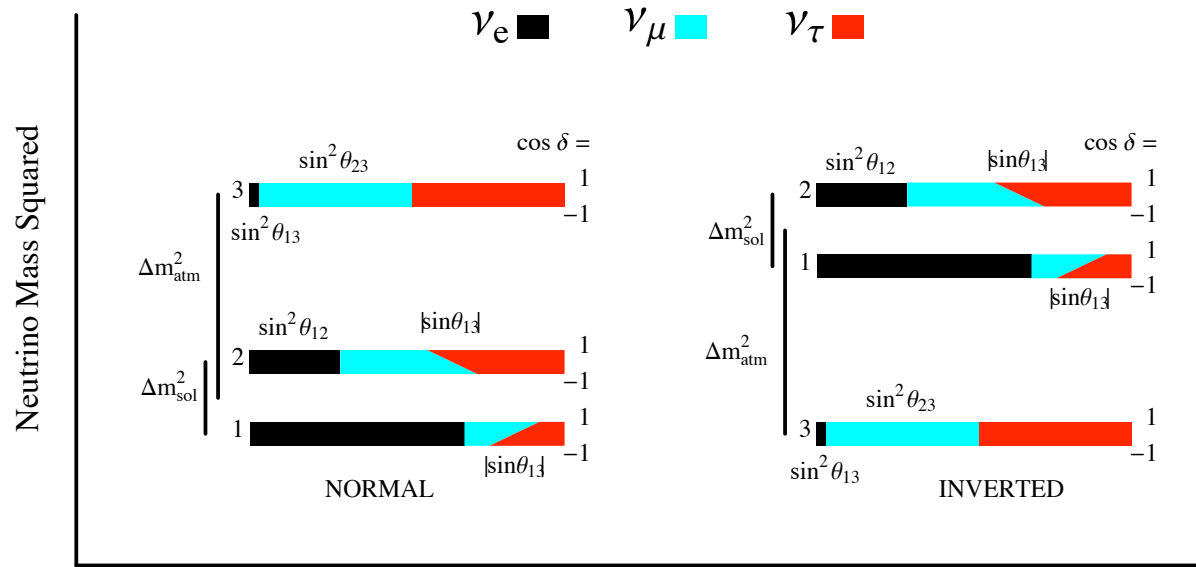
Credits:

For T2K: Aihara P5 talk

For NOvA: Karol Lang NO-VE 2007 talk

# Mixings:

$$|U_{\alpha i}|^2$$

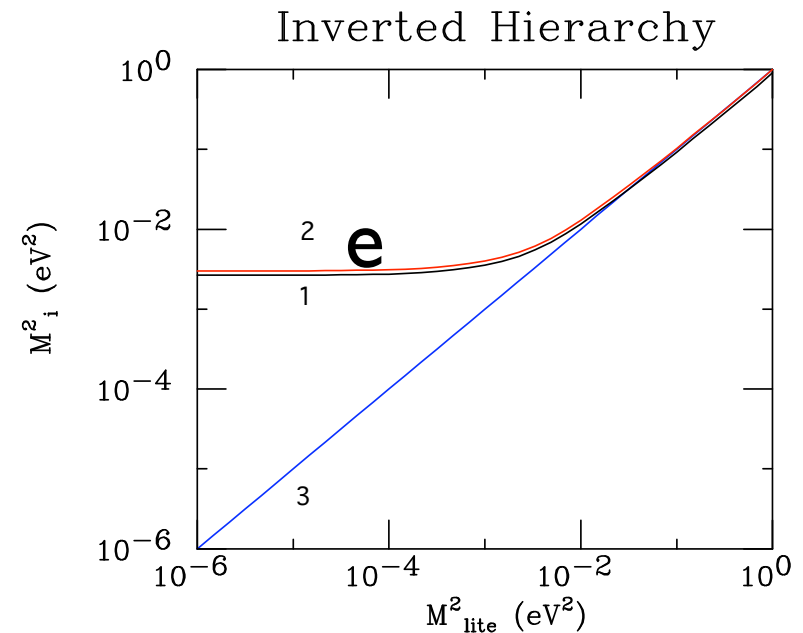
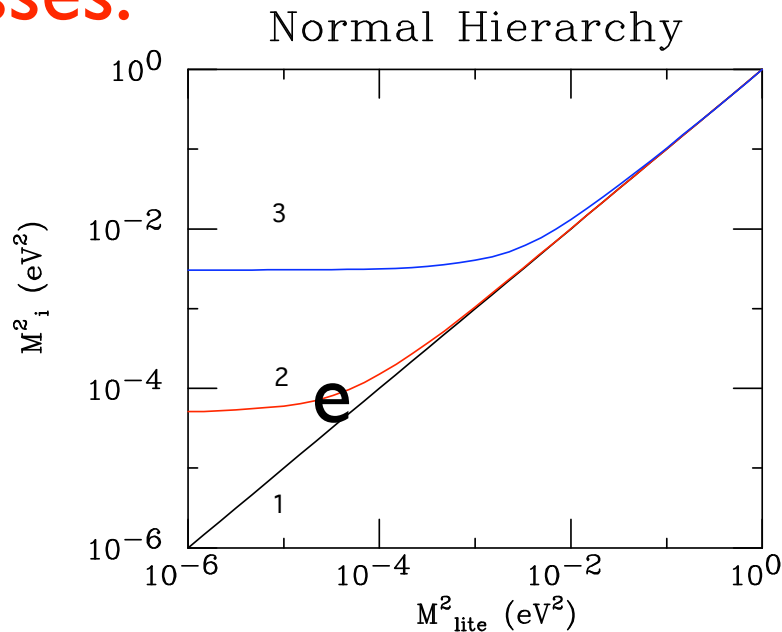


Less than  
4%  $\nu_e$   
in the 3 state!

Fractional Flavor Content varying  $\cos \delta$

CPT:  $\delta \Leftrightarrow -\delta$  Invariant!

# Masses:



States 1 and 2 are  $\nu_e$  rich.

# Long Baseline $\nu_\mu \rightarrow \nu_e$ or $\nu_e \rightarrow \nu_\mu$

- **SUPERBEAMS: (0.4 to 4 MW)**

- Counting Expts (3 ways)
- Spectrum Measurement

- **NEW NEUTRINO BEAMS**

- Neutrino Factory (muon storage ring)
- High Gamma Beta Beams

# Vacuum LBL:

$$\nu_\mu \longrightarrow \nu_e$$

amplitude:

$$\begin{aligned} \mathcal{A}(\nu_\mu \rightarrow \nu_e) = & U_{\mu 3}^* U_{e 3} e^{-im_3^2 L/2E} + U_{\mu 2}^* U_{e 2} e^{-im_2^2 L/2E} \\ & + U_{\mu 1}^* U_{e 1} e^{-im_1^2 L/2E} \end{aligned}$$

eliminate last term using unitarity:

$$U_{\mu 1}^* U_{e 1} + U_{\mu 2}^* U_{e 2} + U_{\mu 3}^* U_{e 3} = 0$$

$$\mathcal{A}(\nu_\mu \rightarrow \nu_e) = U_{\mu 3}^* U_{e 3} \sin \Delta_{31} e^{-i\Delta_{32}} + U_{\mu 2}^* U_{e 2} \sin \Delta_{21}$$

and  $\Delta_{ij} \equiv \delta m_{ij}^2 L/4E$  is the kinematical phase:

$$\nu_{\mu} \longrightarrow \nu_e$$

U=MNS matrix

$$P_{\mu \rightarrow e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$

$$\Delta_{ij} = |\delta m_{ij}^2| L / 4E$$

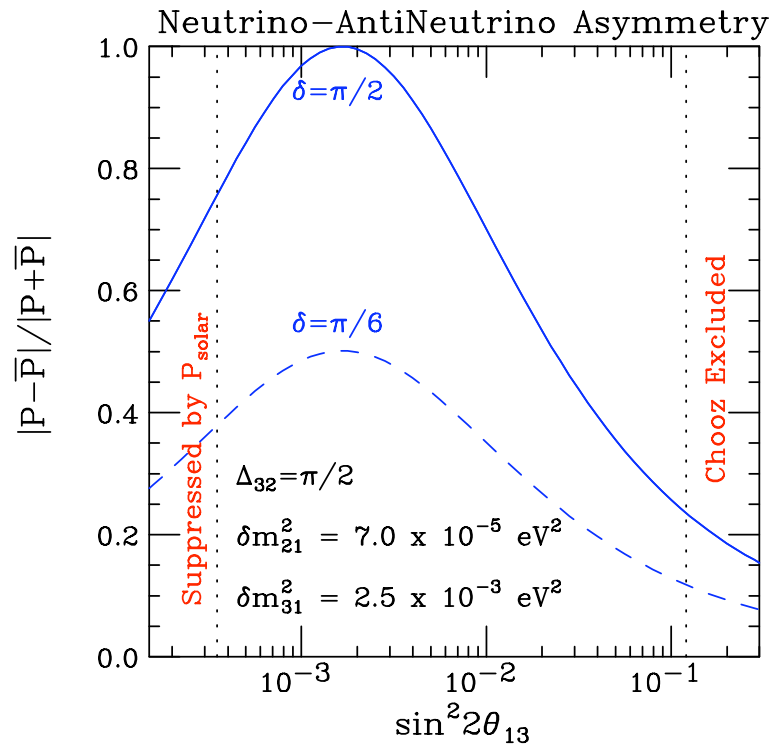
CP violation !!!

where  $\sqrt{P_{atm}} = \sin \theta_{23} \sin 2\theta_{13} \sin \Delta_{31}$

and  $\sqrt{P_{sol}} = \cos \theta_{23} \sin 2\theta_{12} \sin \Delta_{21}$

$$P_{\mu \rightarrow e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$

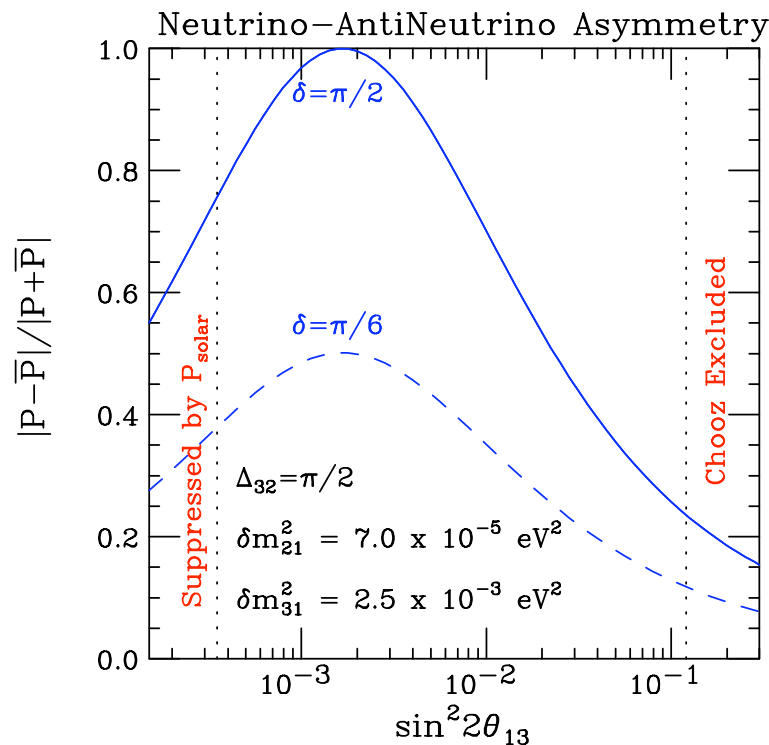
Asymmetry  
Peaks:



$$\sqrt{P_{atm}} = \sqrt{P_{sol}}$$

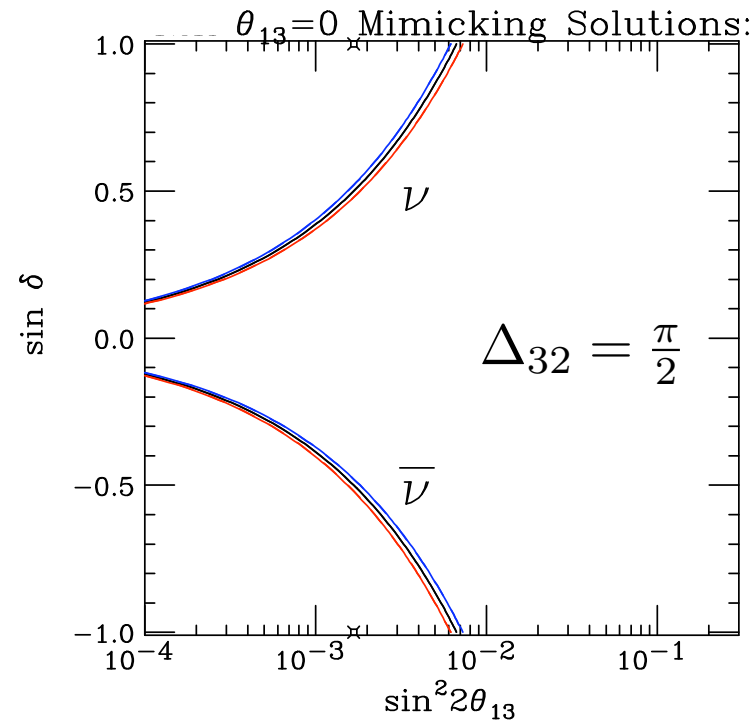
$$P_{\mu \rightarrow e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$

Asymmetry  
Peaks:



$$\sqrt{P_{atm}} = \sqrt{P_{sol}}$$

Zero Mimicking  
Solutions:  $P_{\mu \rightarrow e} = P_{sol}$



$$\sqrt{P_{atm}} = -2\sqrt{P_{sol}} \cos(\Delta_{32} \pm \delta)$$

$\nu_\mu \rightarrow \nu_e$   
with MATTER

$$P_{\mu \rightarrow e} \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} \pm \delta)} + \sqrt{P_{sol}} \right|^2$$

$\{\delta m^2 \sin 2\theta\} \text{ is invariant}$

where  $\sqrt{P_{atm}} = \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)} \Delta_{31}$

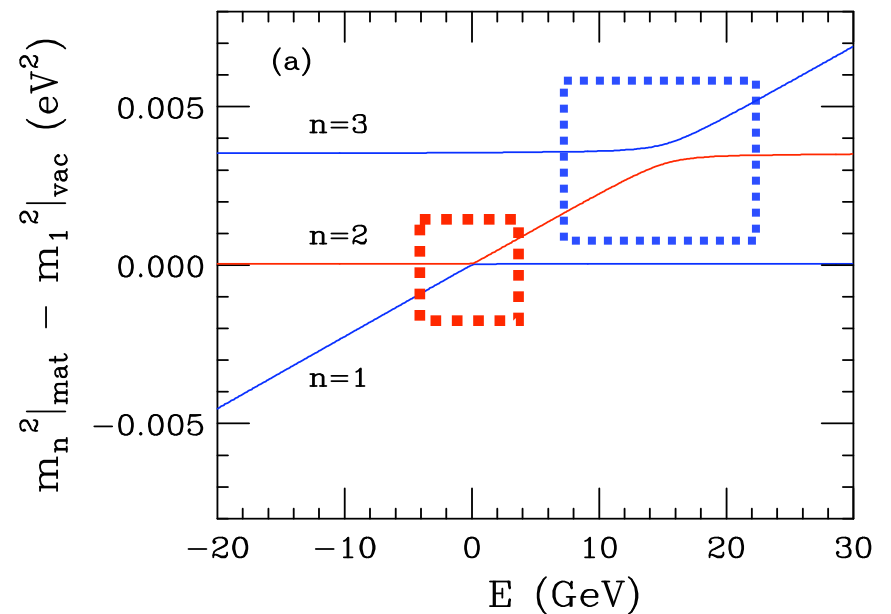
in vac  $\sin \Delta_{31}$

and  $\sqrt{P_{sol}} = \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$

in vac  $\sin \Delta_{21}$

$$a = G_F N_e / \sqrt{2} = (4000 \text{ km})^{-1},$$

$$\pm = \text{sign}(\delta m_{31}^2) \quad \Delta_{ij} = |\delta m_{ij}^2| L / 4E$$



# Counting Expts near First Osc. Max.

T2K

## JHF → Super-Kamiokande

- ✓ 295 km baseline
- ✓ Super-Kamiokande:
  - 22.5 kton fiducial
  - Excellent  $e/\mu$  ID
  - Additional  $\pi^0/e$  ID
- ✓ Hyper-Kamiokande
  - 20× fiducial mass of SuperK
- ✓ Matter effects small
- ✓ Study using fully simulated and reconstructed data



2.0, 2.5 or 3.0 deg

# Counting Expts near First Osc. Max.

T2K

## JHF → Super-Kamiokande

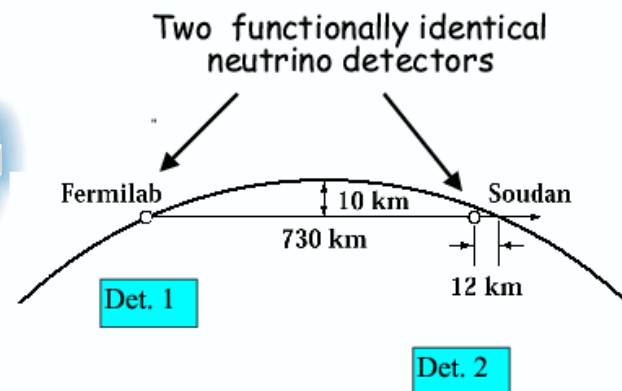
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2.0, 2.5

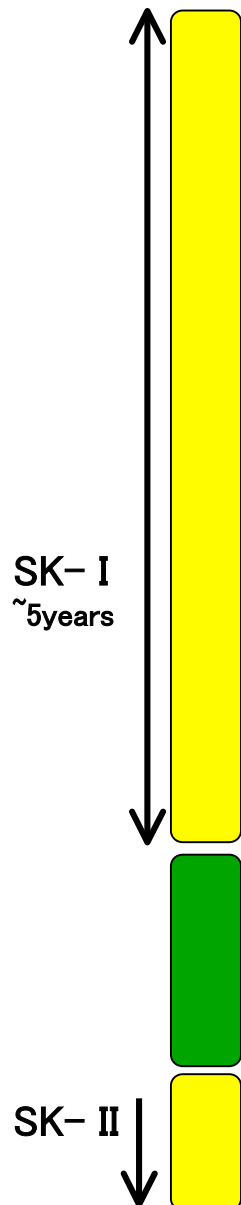
## The NUMI Beamline

NOVA

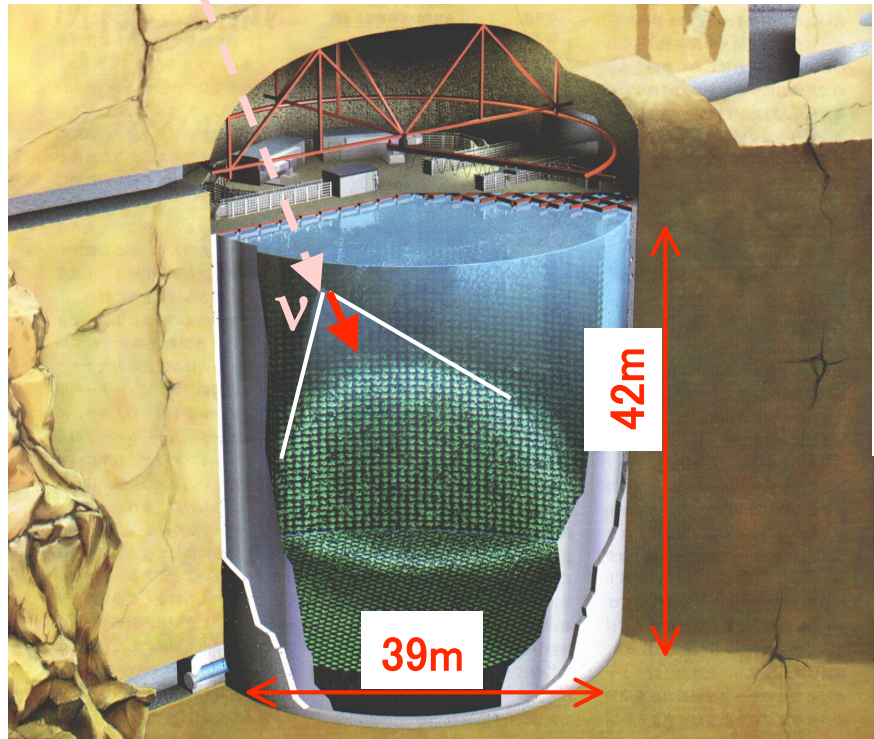


10, 12 14 km

# Water Cherenkov detector



- 1996.4 Start data taking (SK- I)



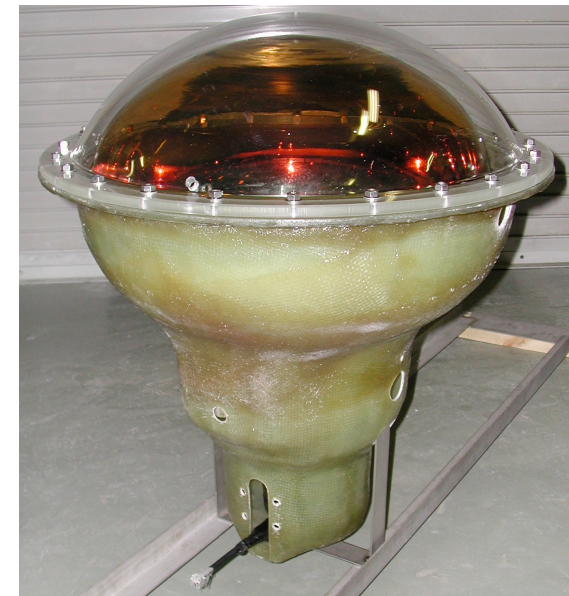
- 2700 w.e. overbuden
- 50,000 ton  
(22,500 ton fid.)
- 11,146 20 inch PMTs
- Photo cathode coverage:  
40% of surface
- 1,885 anti-counter PMTs

- 2001.7 Stop data taking for detector upgrade
- 2001.11 Accident (6777 inner PMTs, 1100 outer PMTs were destroyed)

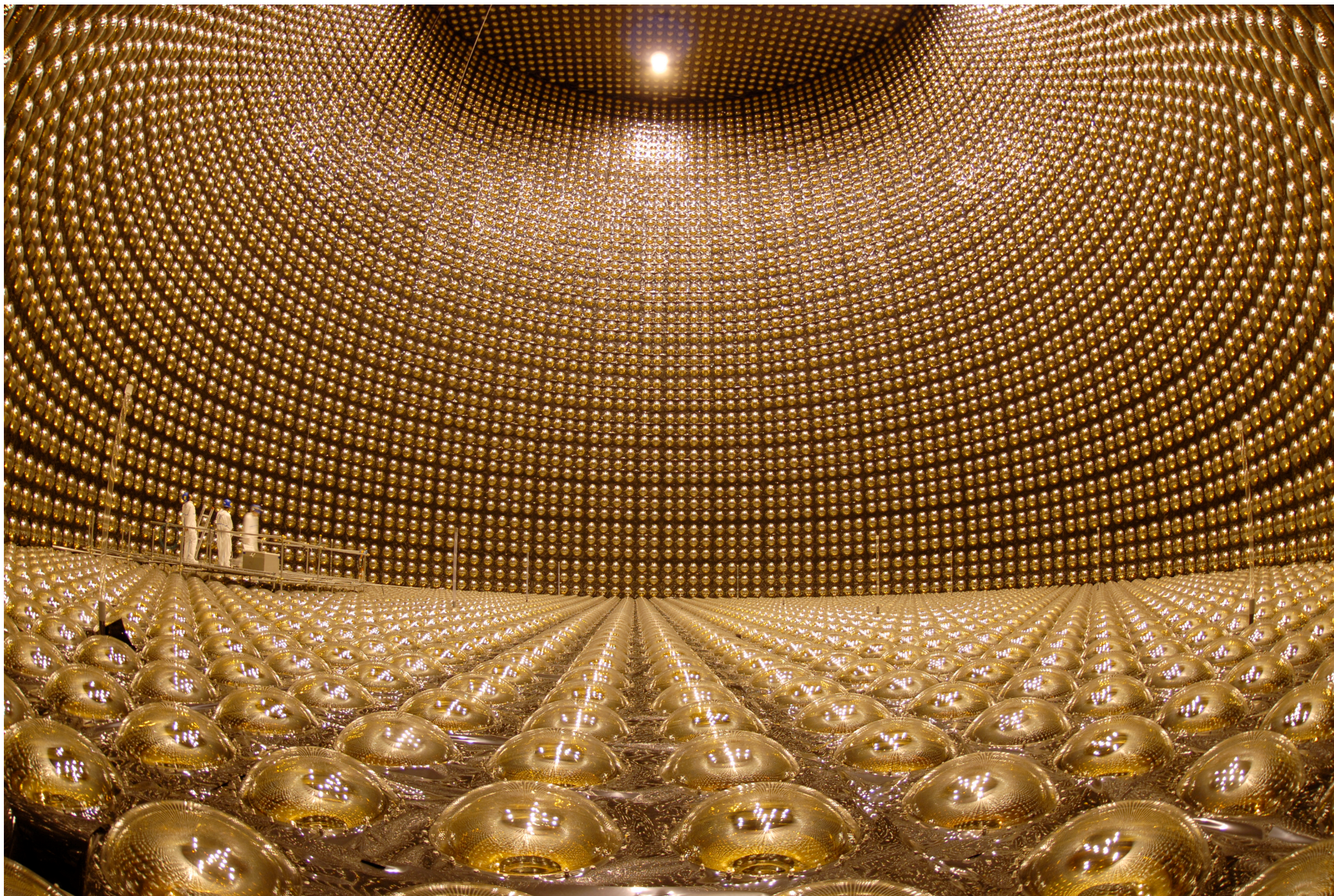
partial reconstruction of the detector

- 2002.10 Resume data taking (SK- II) mostly for K2K  
(photocathode coverage of 20%, 7MeV)

- 2005.10 Start full recovery work

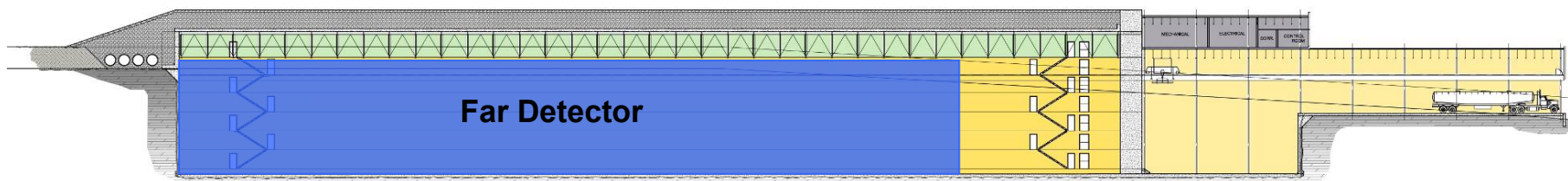
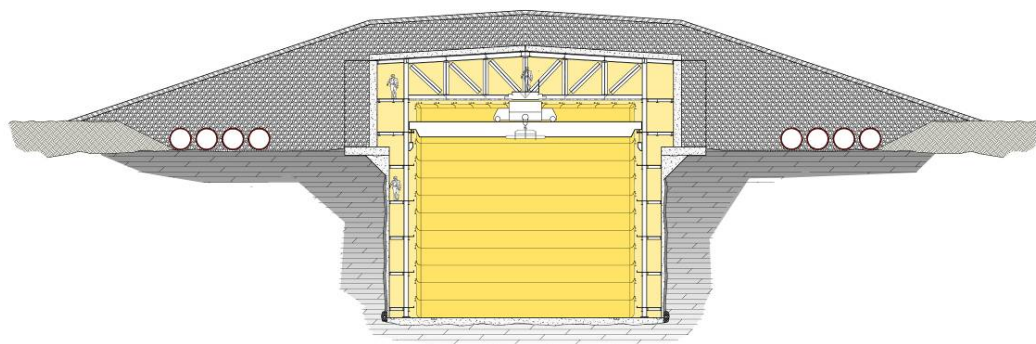
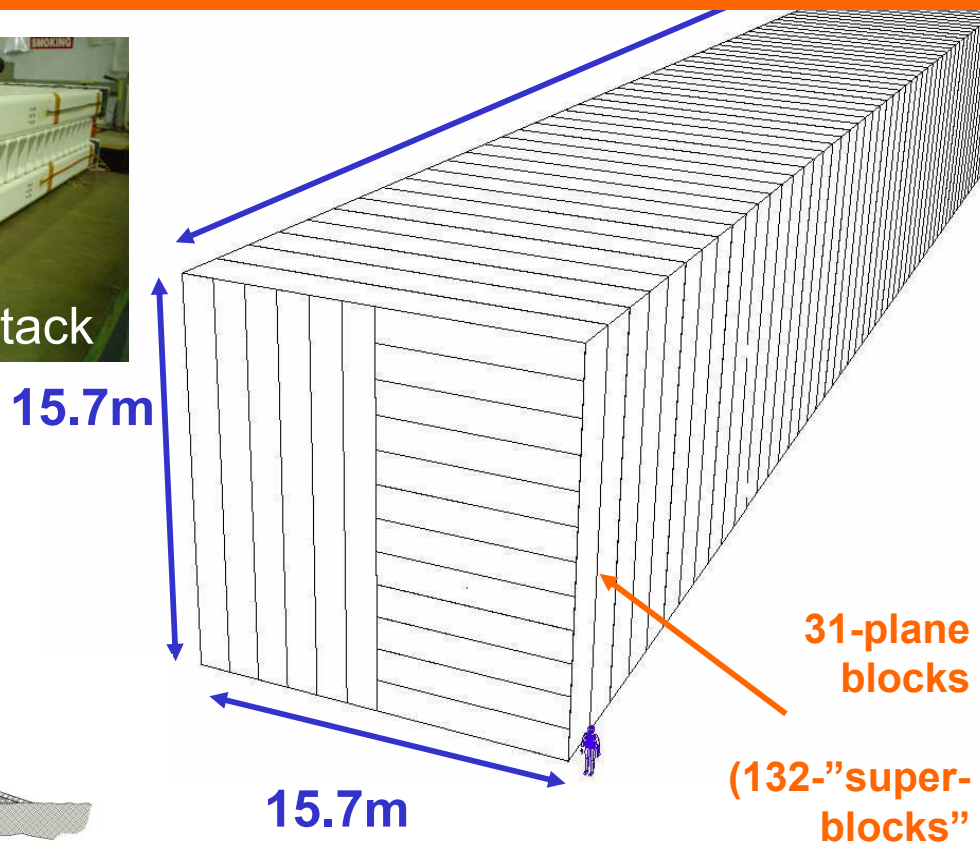


Acrylic + FRP vessel

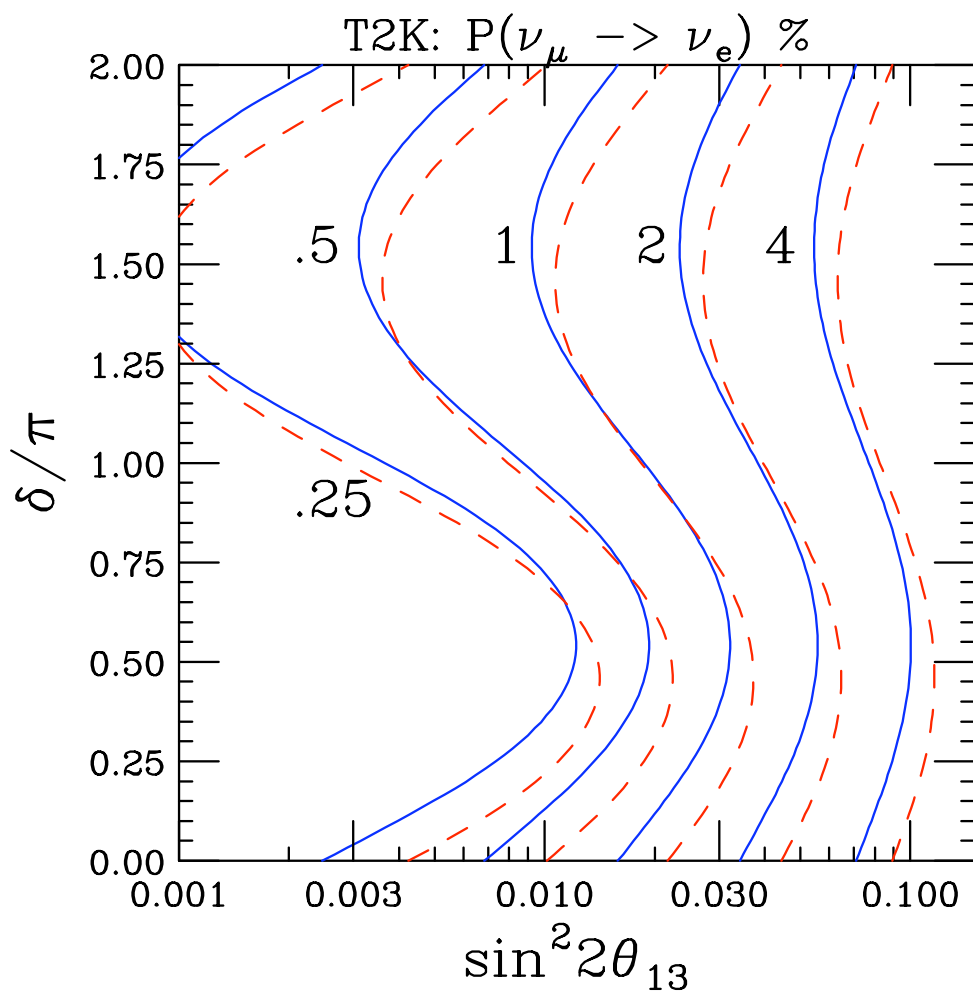


**We will build as much of this as the funding will allow...**

- ❑ TAD = Totally Active Detector  
PVC = passive material
- ❑ mass N kT (N large)
  - ~80% scintillator
  - ~20% PVC extrusions
- ❑ Modular structure
  - 32 cells/extrusion
  - 12 extrusions/plane
  - 1984 planes
- ❑ Cell dimensions:  
3.9 cm x 6 cm x 15.7m
- ❑ U-shaped 0.7 mm WLS fiber into APD



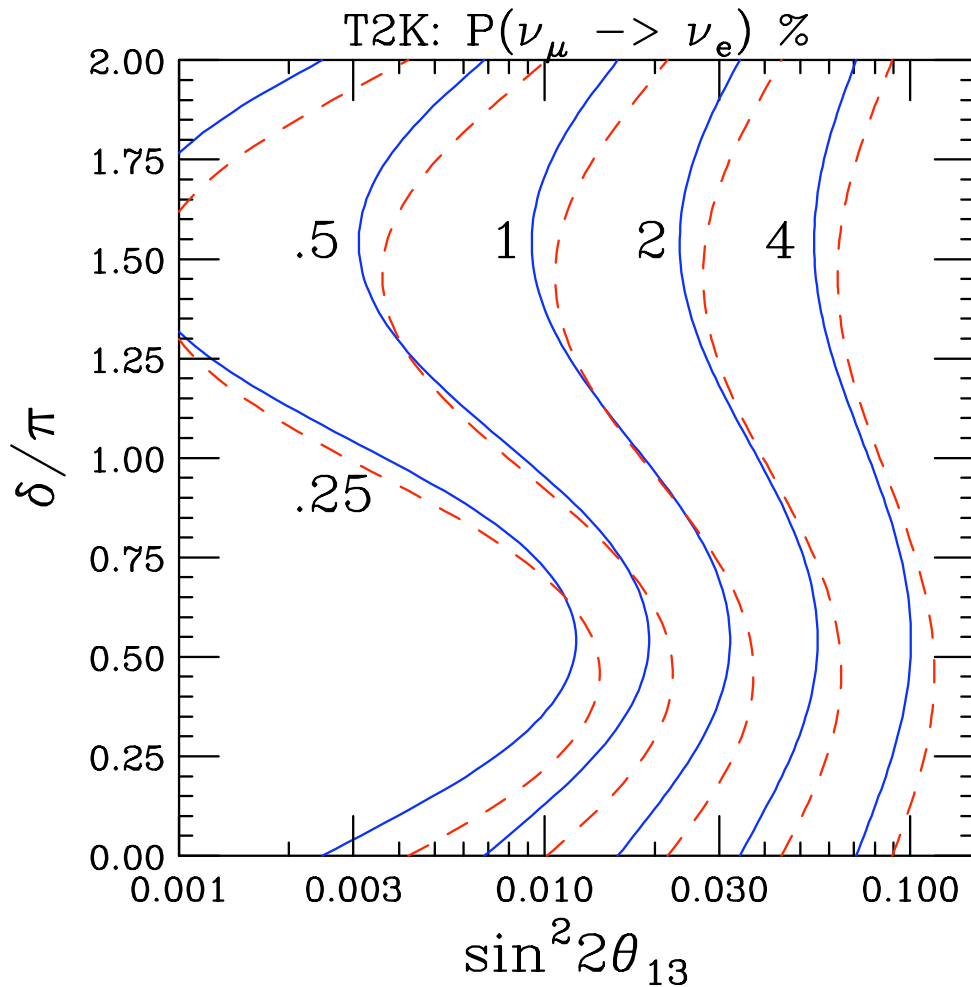
# T2K:



$$\delta m_{31}^2 > 0$$

$$\delta m_{31}^2 < 0$$

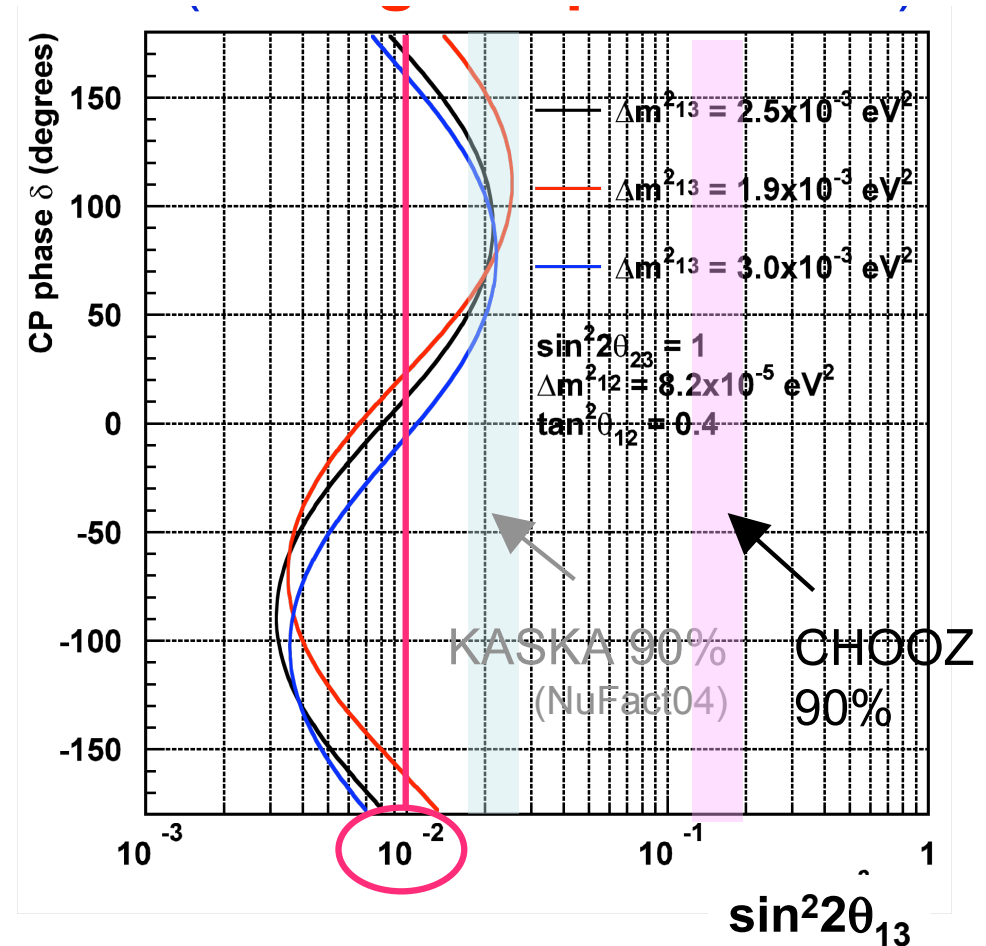
# T2K:



$$\delta m_{31}^2 > 0$$

$$\delta m_{31}^2 < 0$$

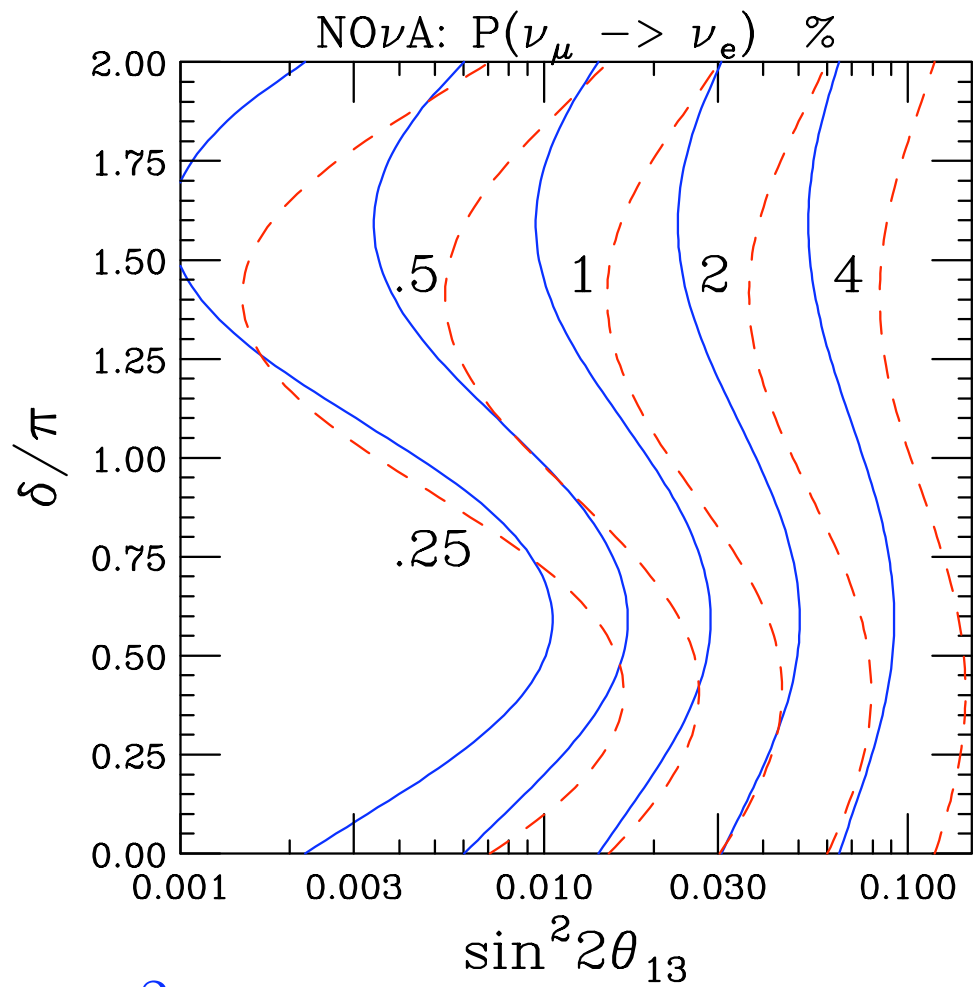
## Aihara for T2K, P5 talk



Phase I

Sensitivity approx 0.5%

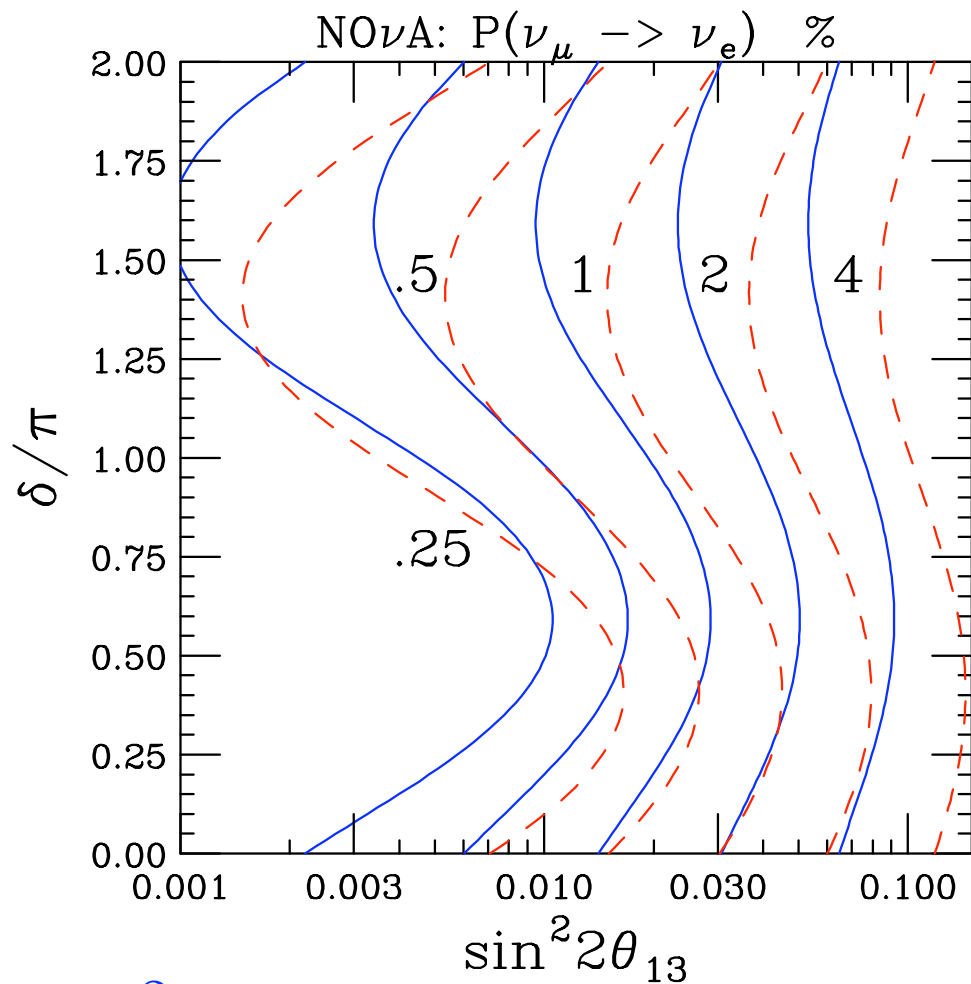
# NO $\nu$ A:



$$\delta m_{31}^2 > 0$$

$$\delta m_{31}^2 < 0$$

# NOvA:



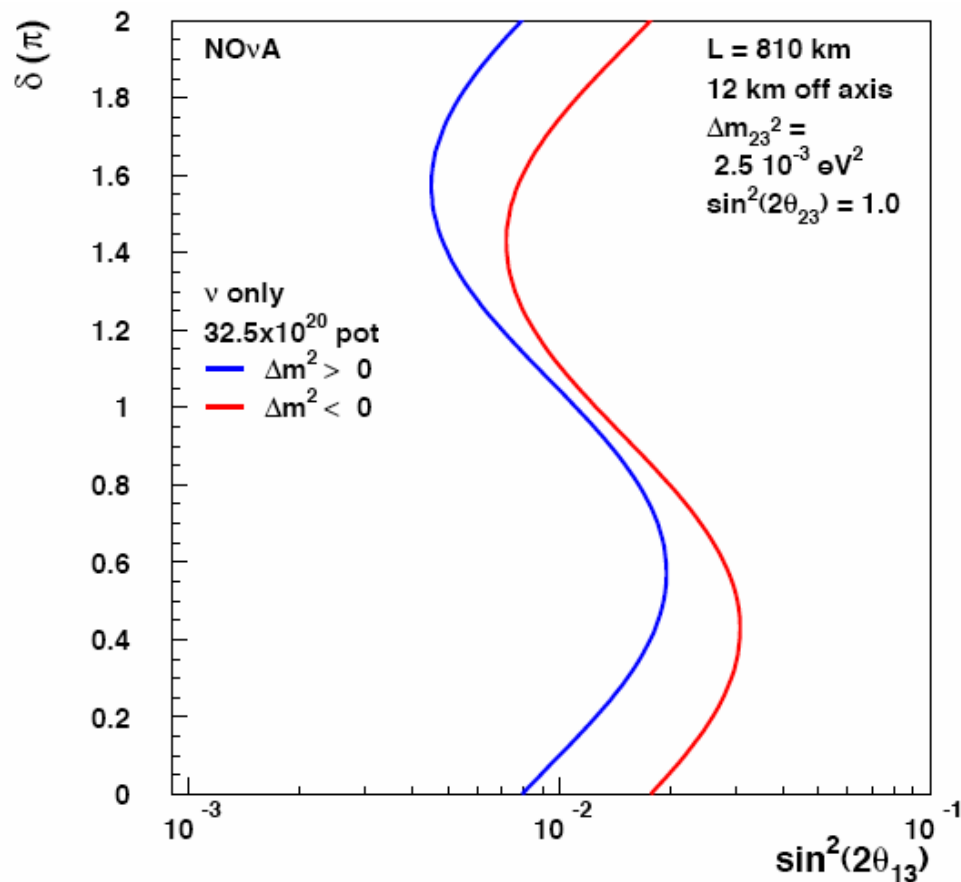
$$\delta m_{31}^2 > 0$$

$$\delta m_{31}^2 < 0$$

Phase I

Sensitivity approx 0.5%

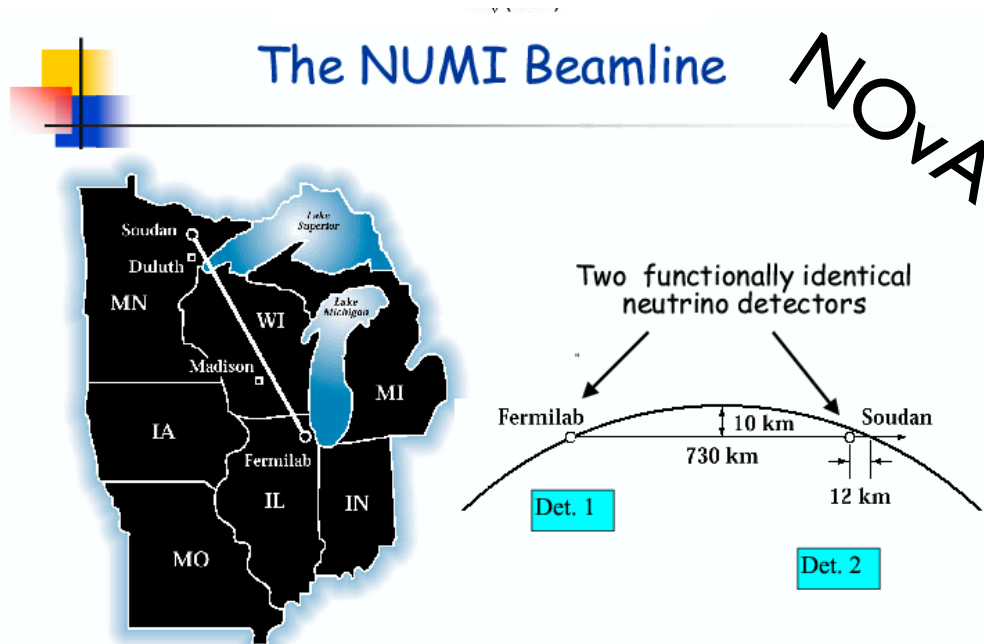
## NOvA @ NO-VE 2007



5 years with  $\nu$  only run

# Counting Expts at First Osc. Max.

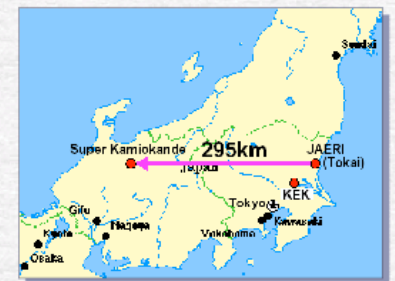
- Neutrino  $\nu$  Anti-Neutrino One Expt.
- Neutrino  $\nu$  Neutrino Two Expts Different L's and EQUAL E/L's
- Neutrino  $\nu$  Anti-Neutrino Two Expts Different L's



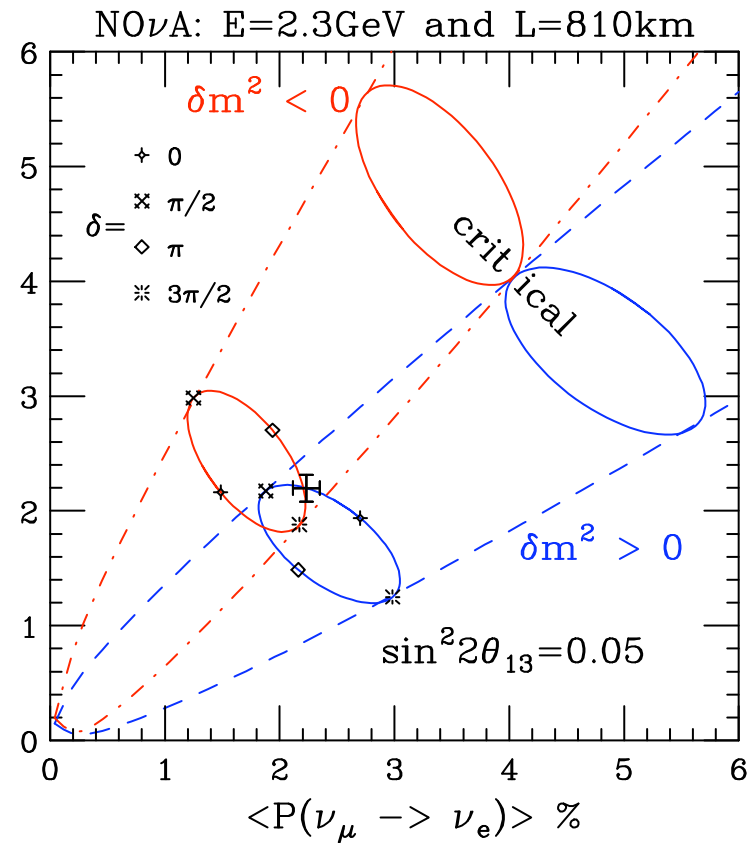
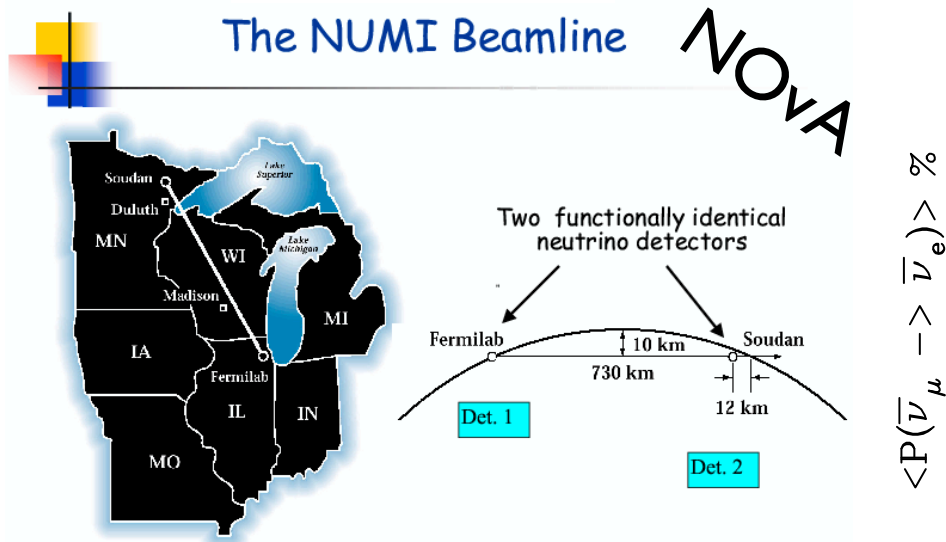
T2K

## JHF $\rightarrow$ Super-Kamiokande

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# Neutrino $\nu$ Anti-Neutrino One Expt.



in the overlap region

$$\langle \sin \delta \rangle_+ - \langle \sin \delta \rangle_- = 2\langle \theta \rangle / \theta_{crit} \approx 1.4 \sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

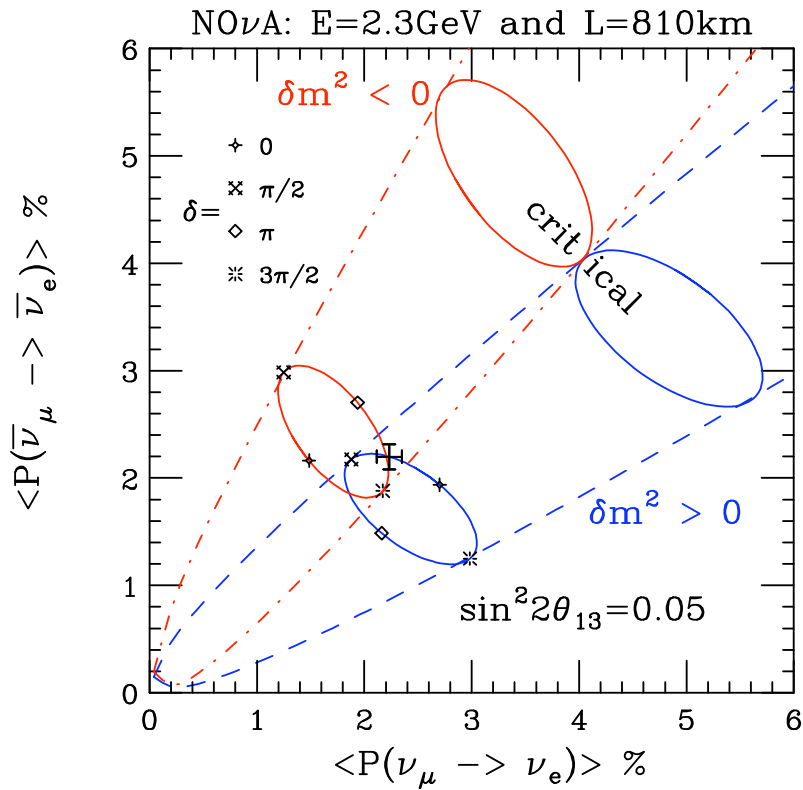
exact along diagonal --- approximately true throughout the overlap region!!!

$$\theta_{crit} = \frac{\pi^2}{8} \frac{\sin 2\theta_{12}}{\tan \theta_{23}} \frac{\delta m_{21}^2}{\delta m_{31}^2} \left( \frac{4\Delta^2/\pi^2}{1-\Delta \cot \Delta} \right) / (aL) \sim 1/6$$

i.e.  $\sin^2 2\theta_{crit} = 0.10$

O. Mena + SP  
hep-ph/0408070

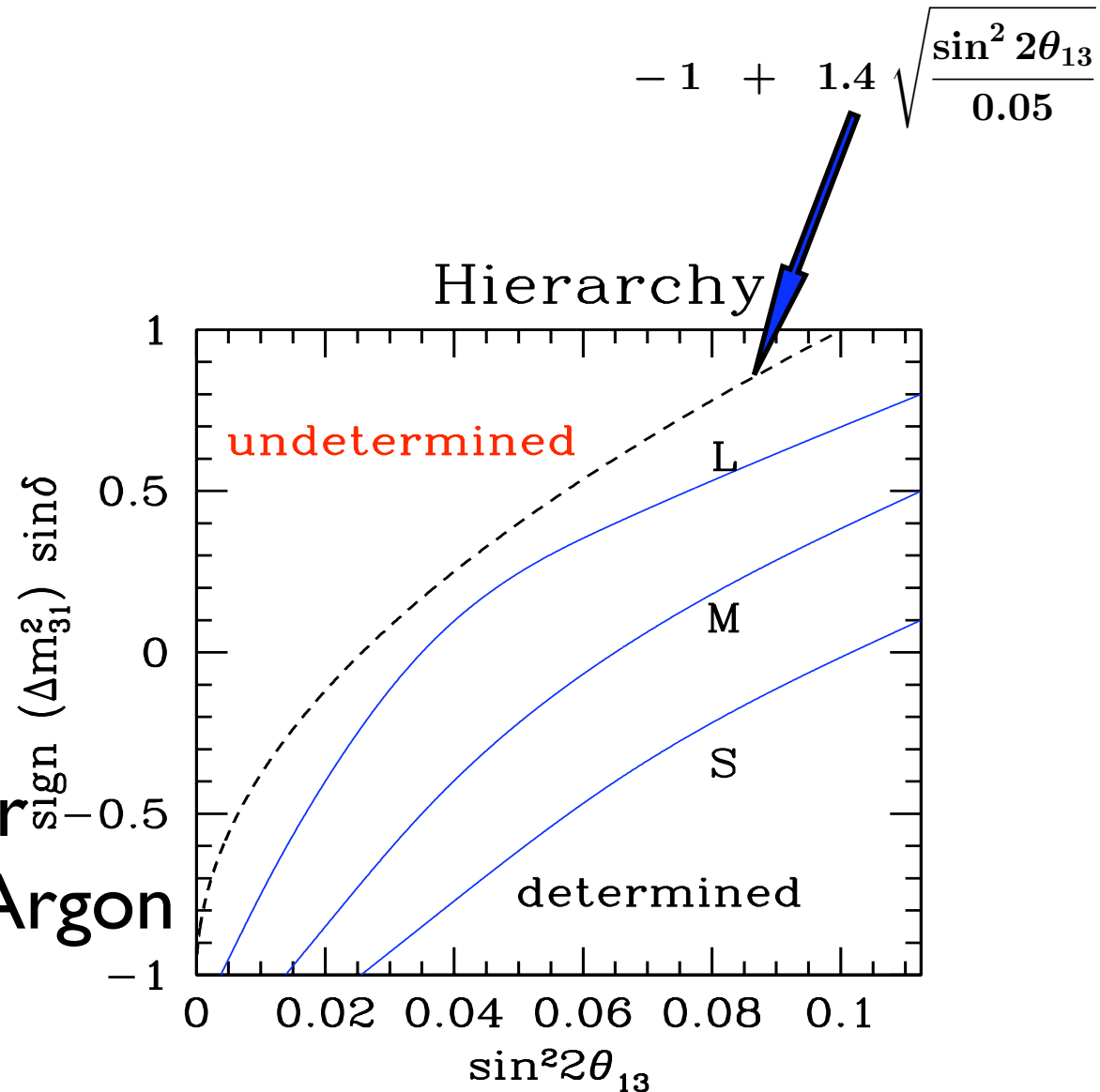
# NOvA:



S: 4 +4 yrs

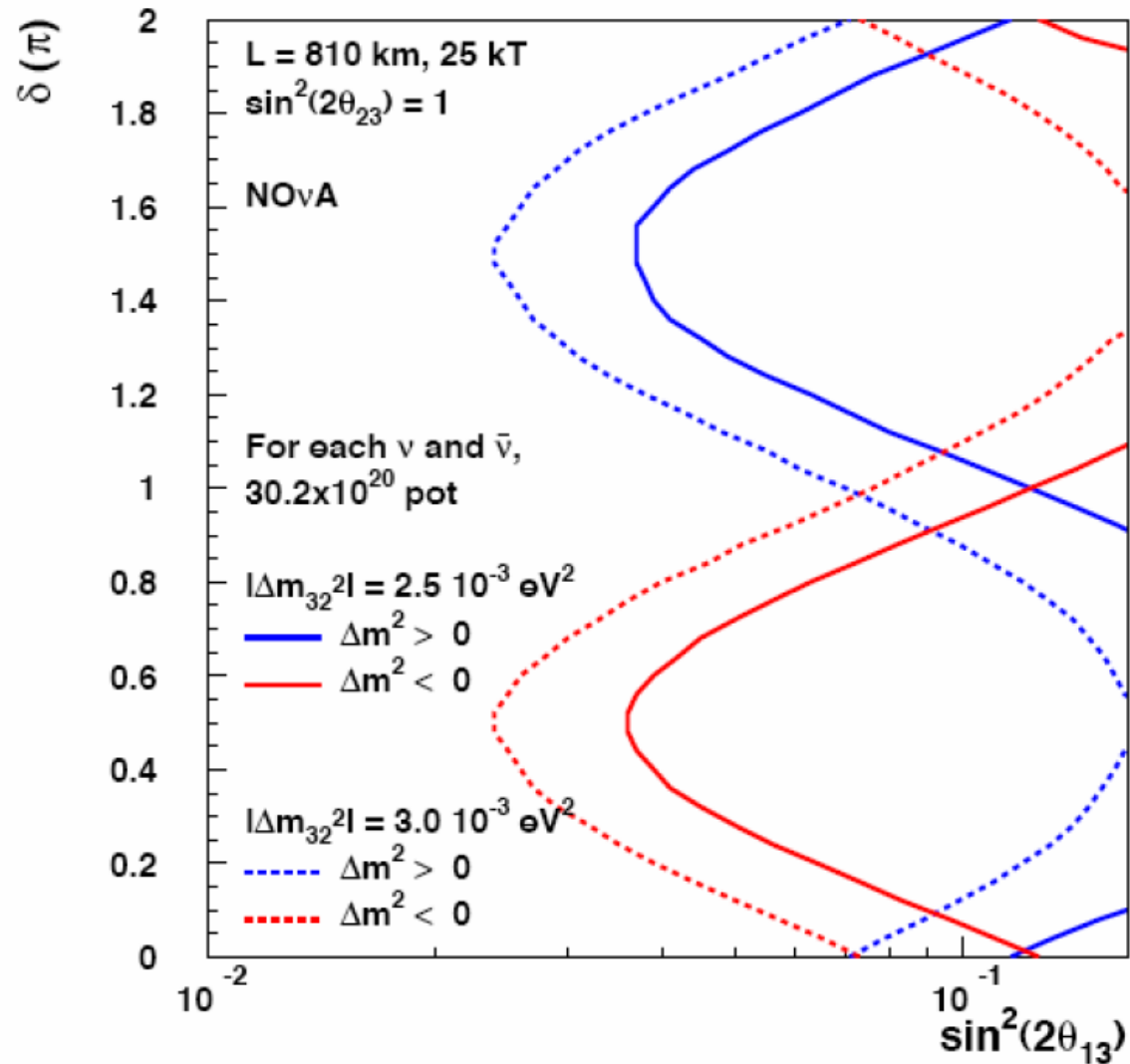
M (=5\*S): Proton Driver

L (=5\*M): PD + Liquid Argon



# NOvA:

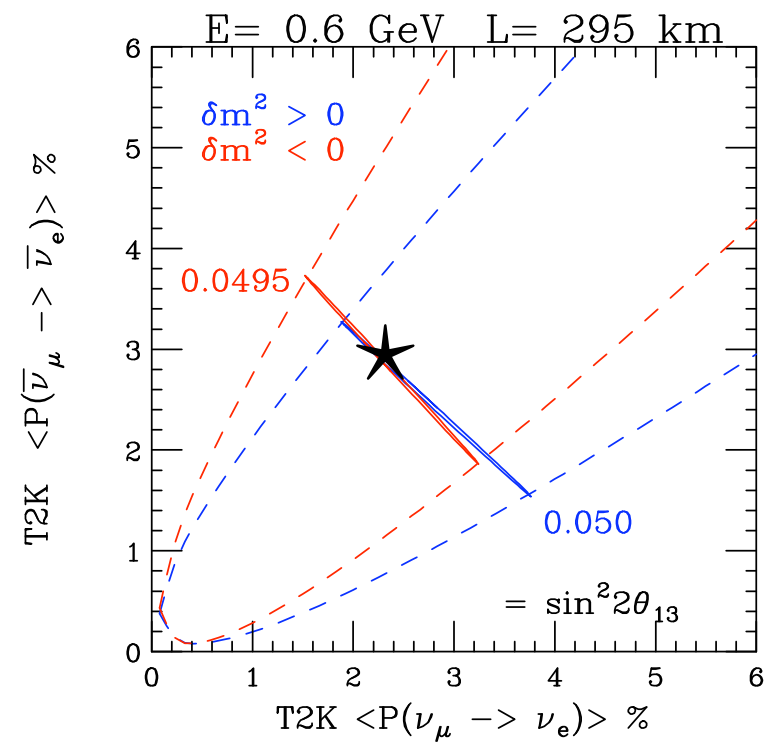
## 95% CL Resolution of the Mass Hierarchy



T2K

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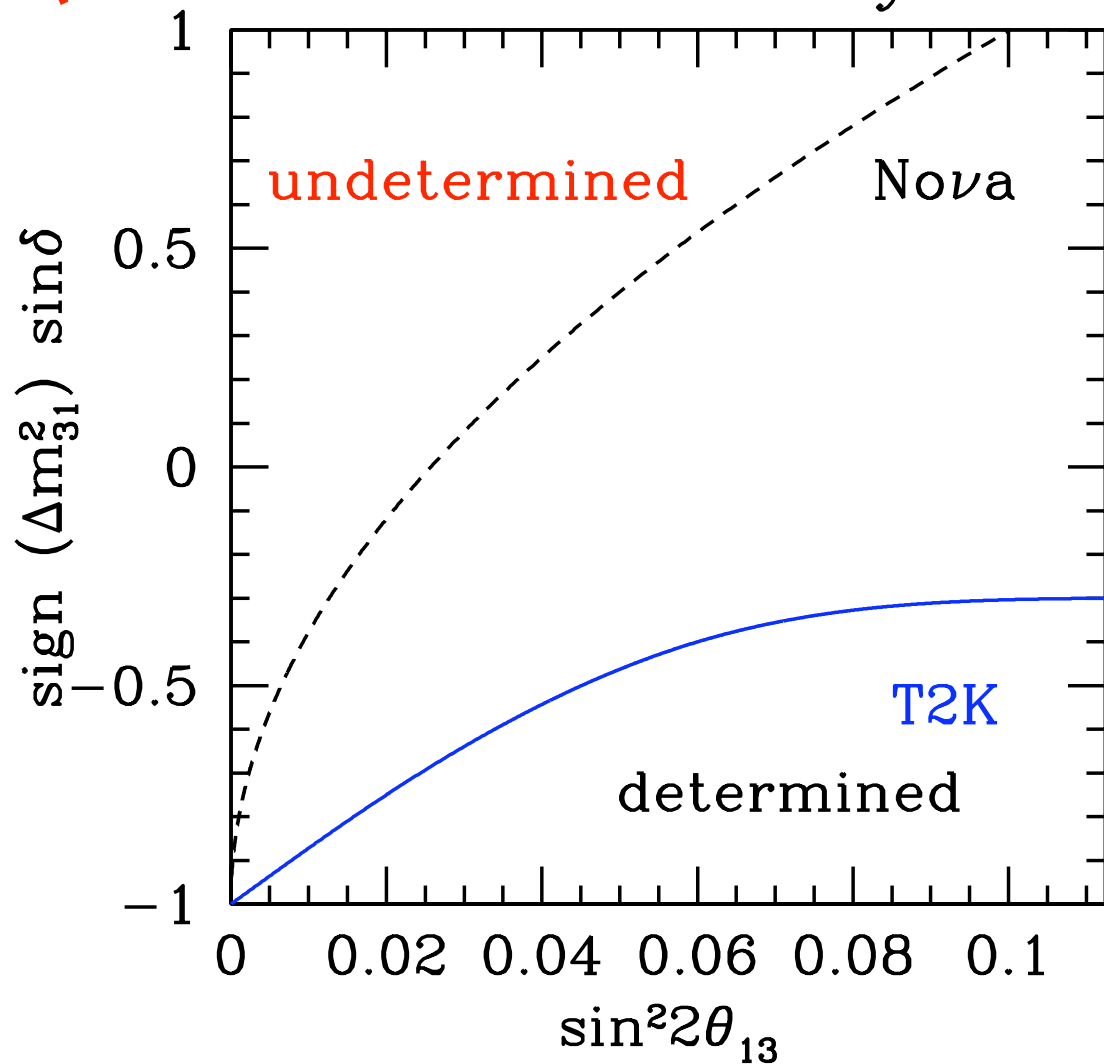


$$\langle \sin \delta \rangle_+ - \langle \sin \delta \rangle_- = 2\langle \theta \rangle / \theta_{crit} \approx 0.47 \sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

$(\rho L)$  for NOvA three times larger than  $(\rho L)$  than T2K.

Potential

Hierarchy



$$-1 + 1.4 \sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

$$-1 + 0.47 \sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

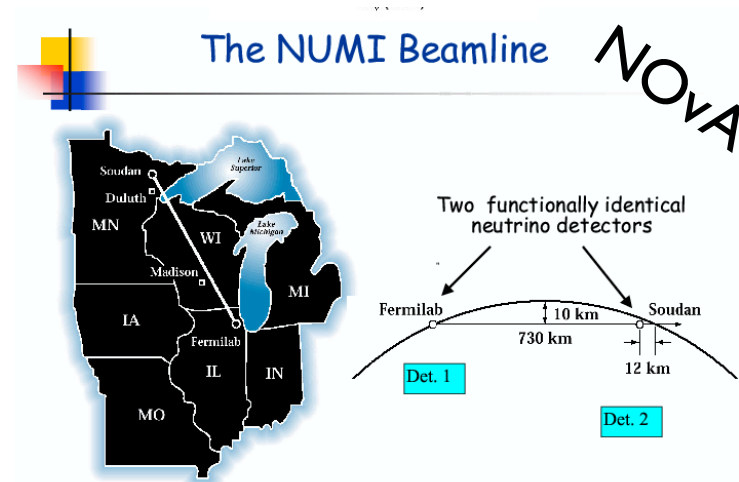
# Neutrino $\nu$ Neutrino Two Expts

## Different L's and EQUAL $\langle E \rangle / L$ 's

T2K

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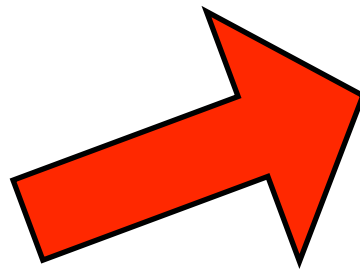


2.5 degrees and 14 km

or

2.0 degrees and 12 km

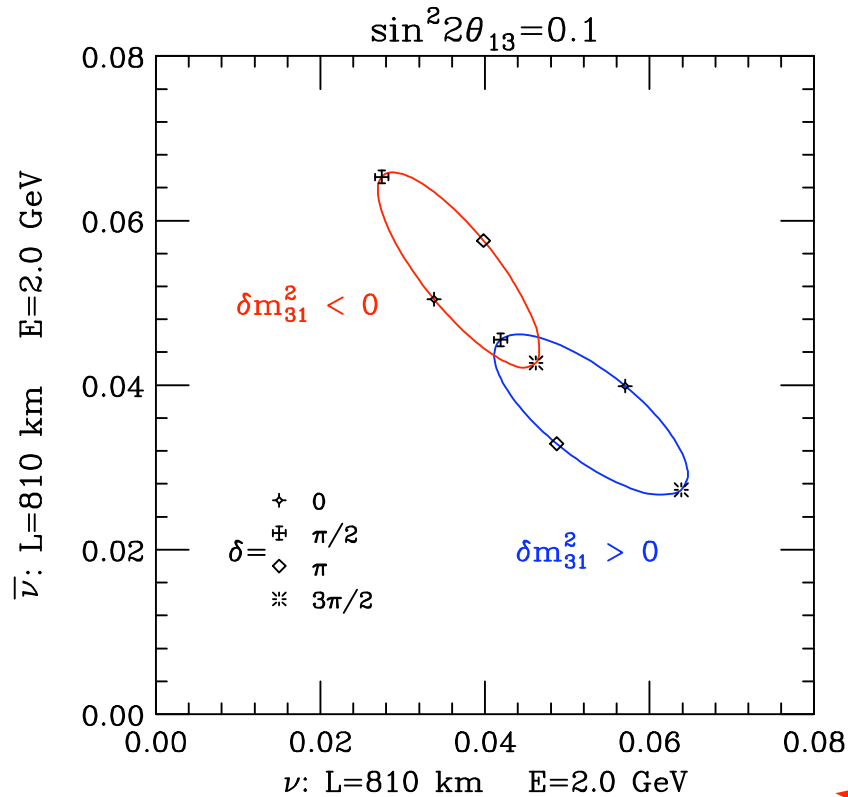
EQUAL  $\langle E \rangle / L$



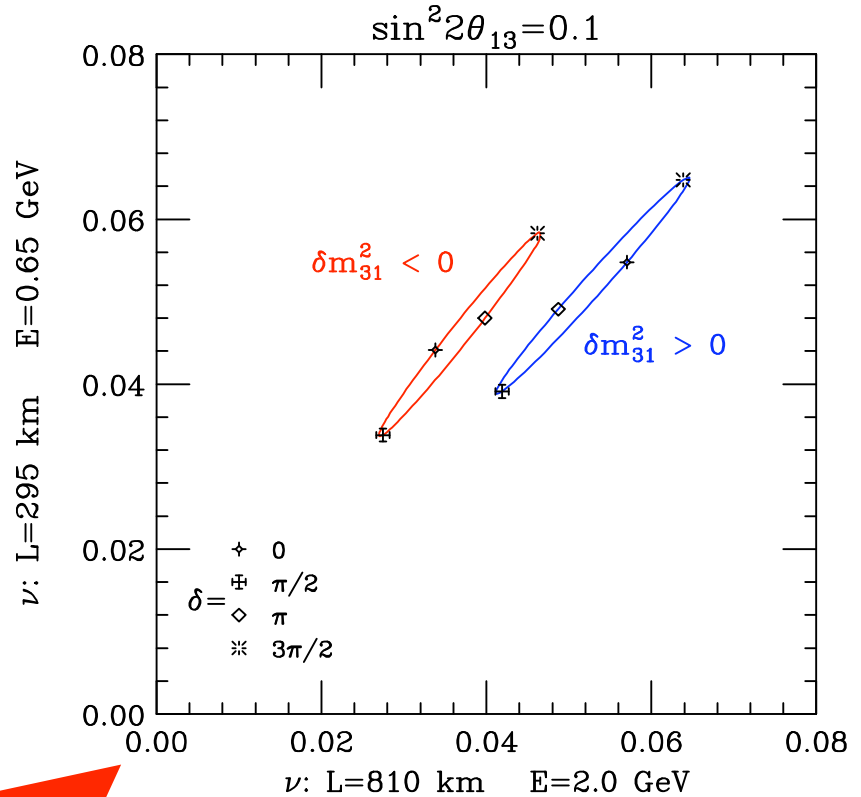
but NOT

2.5 degrees and 12 km

# Bi-Probability nu-antineu    ν    nu-nu



(a) Neutrino-Antineutrino



(b) Neutrino-Neutrino

flat when

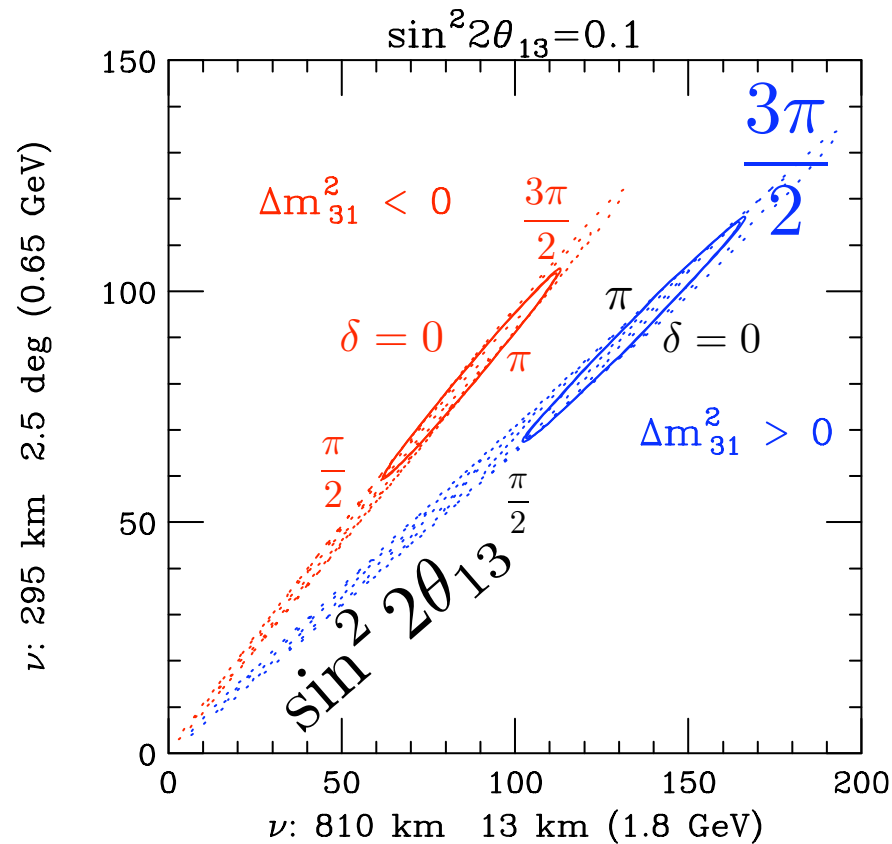
$$\Delta + \bar{\Delta} = \pi$$

flat when

$$P_N(\theta_{13}, \delta) = P_N(\theta_{13}, \delta') \quad \text{and} \quad P_F(\theta_{13}, \delta) = P_F(\theta_{13}, \delta')$$

non-trivial solutions  $\Delta_N = \Delta_F$ ,

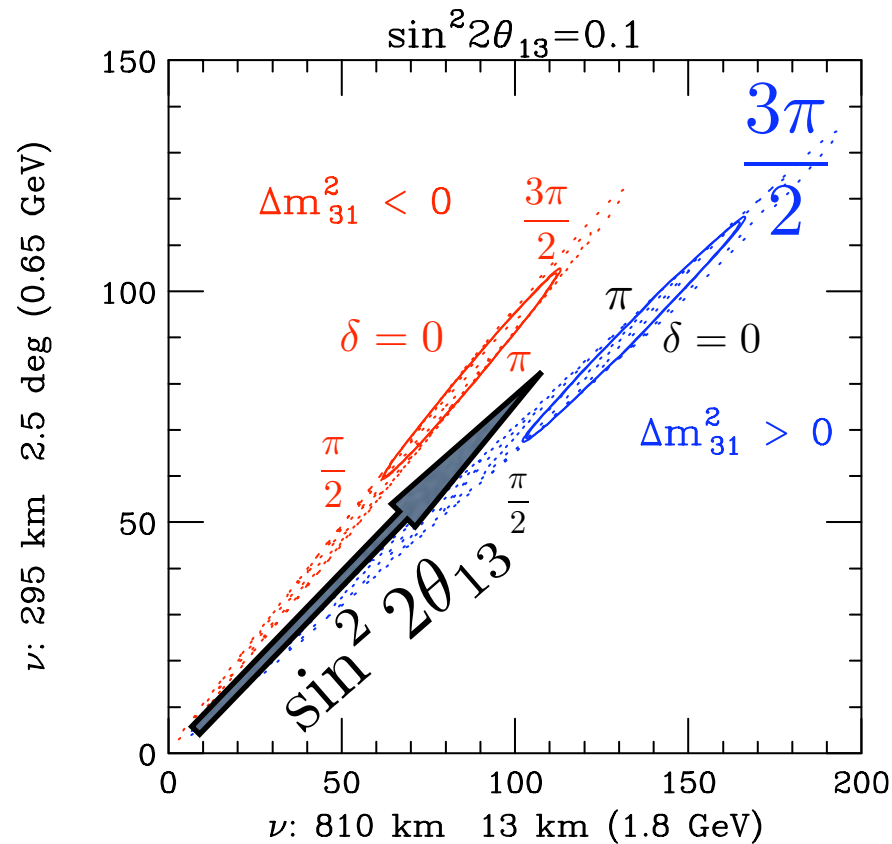
same  $\langle E \rangle / L$ .



Chooz Bound :  $\sin^2 2\theta_{13} = 0.12$

Horiz. separation matter effect for NOvA.

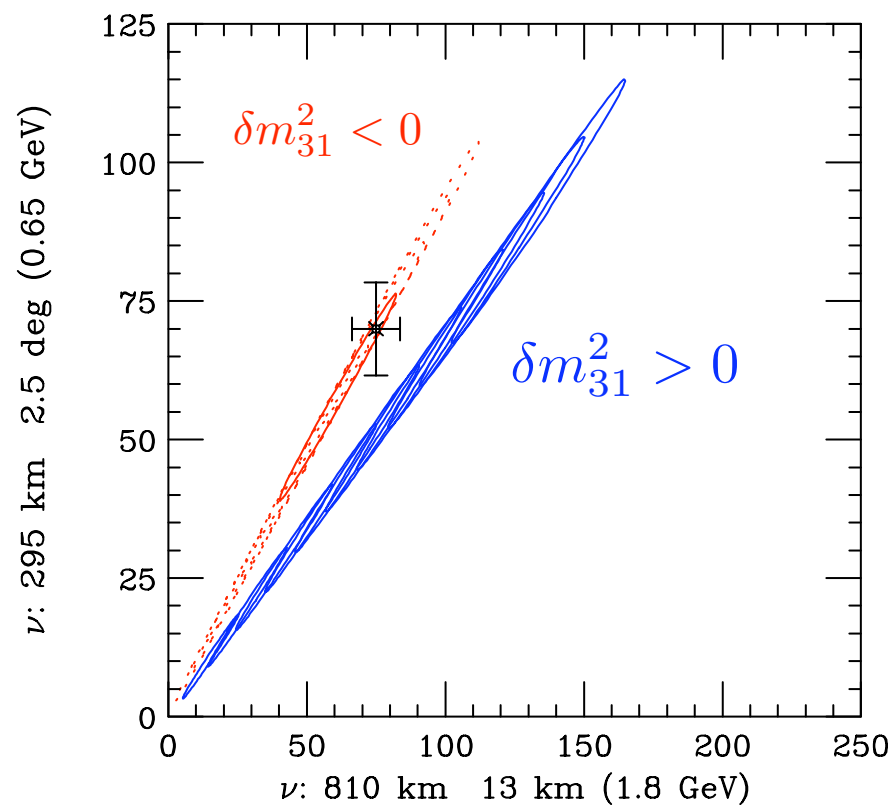
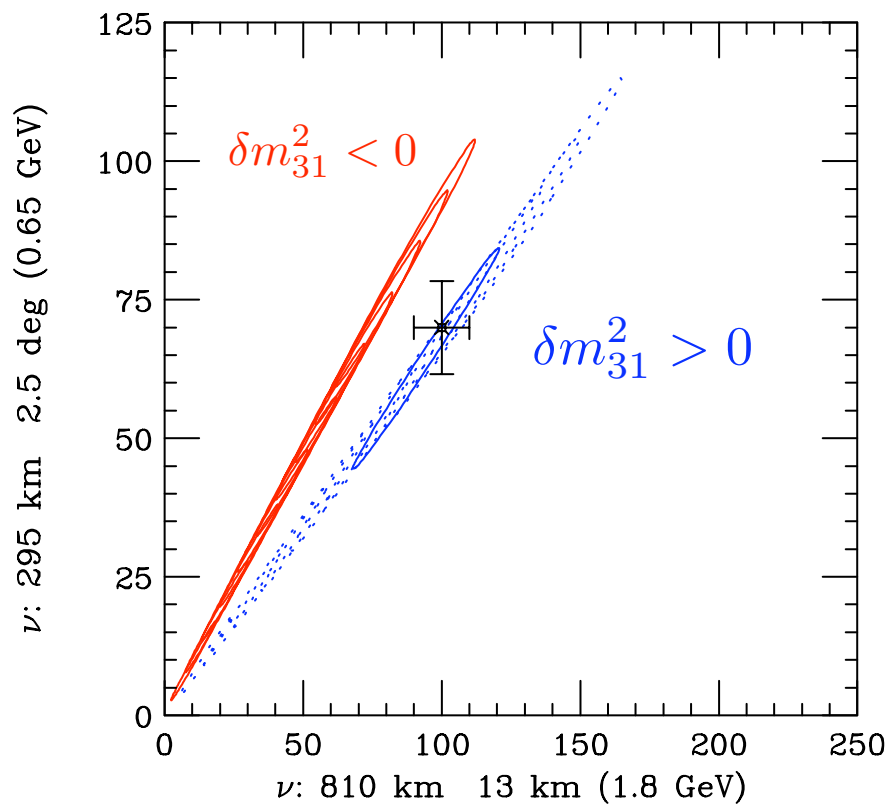
Vert. separation matter effect for T2K.



Horiz. separation matter effect for NOvA.  
 Vert. separation matter effect for T2K.

$$\sin^2 2\theta_{13} = 0.07$$

T2K



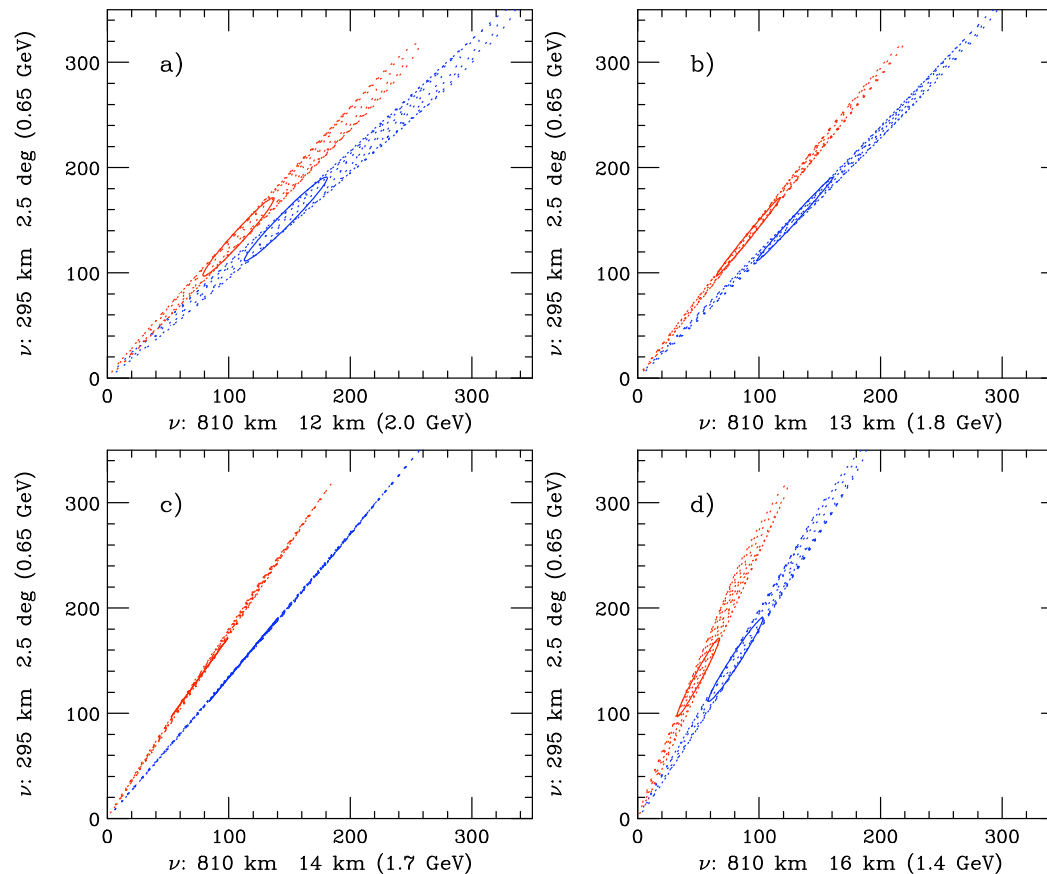
NOvA

# NOvA + T2K Neutrinos Only:

## Bi-Event Plots:

5 yrs

T2K:  
750MW  
22.5kton  
eff=70%



$$\delta m_{31}^2 > 0$$

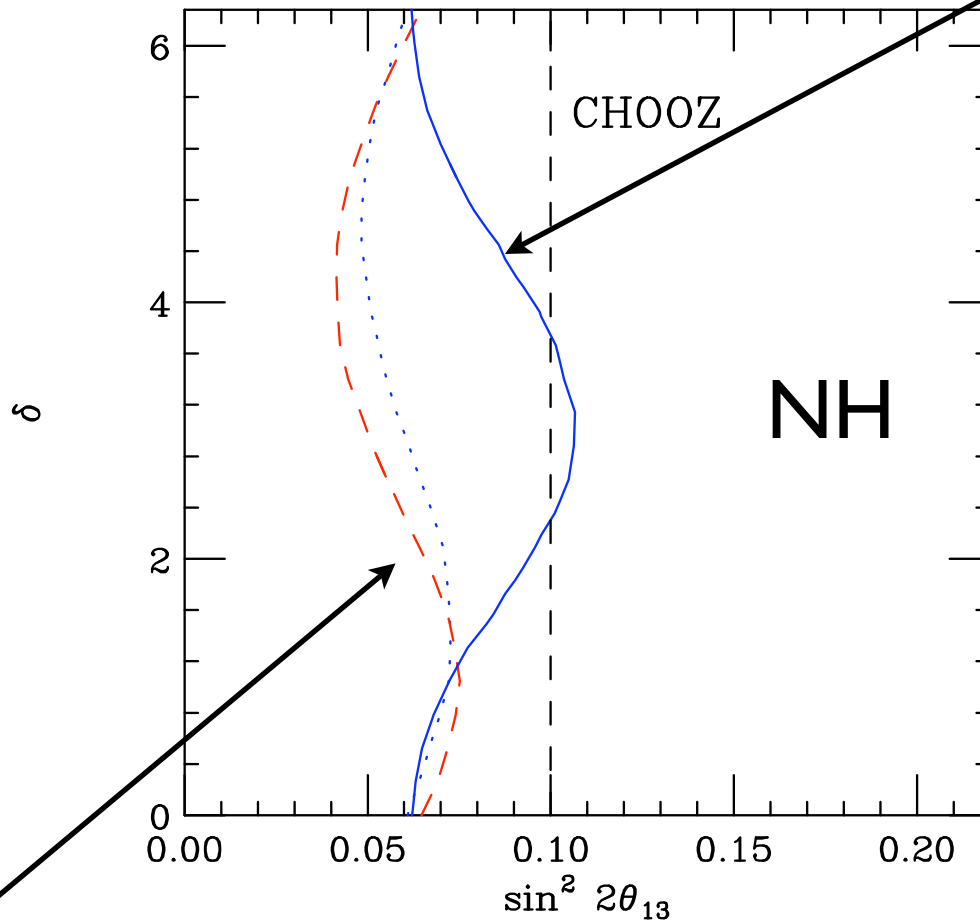
$$\delta m_{31}^2 < 0$$

15% stat.  
hit per step!

NOvA: 400MW  
30kton eff=24%

# Hierarchy Determination using 2 dof: 90% CL

2.5 deg & 12 km



WHY 2 dof ????

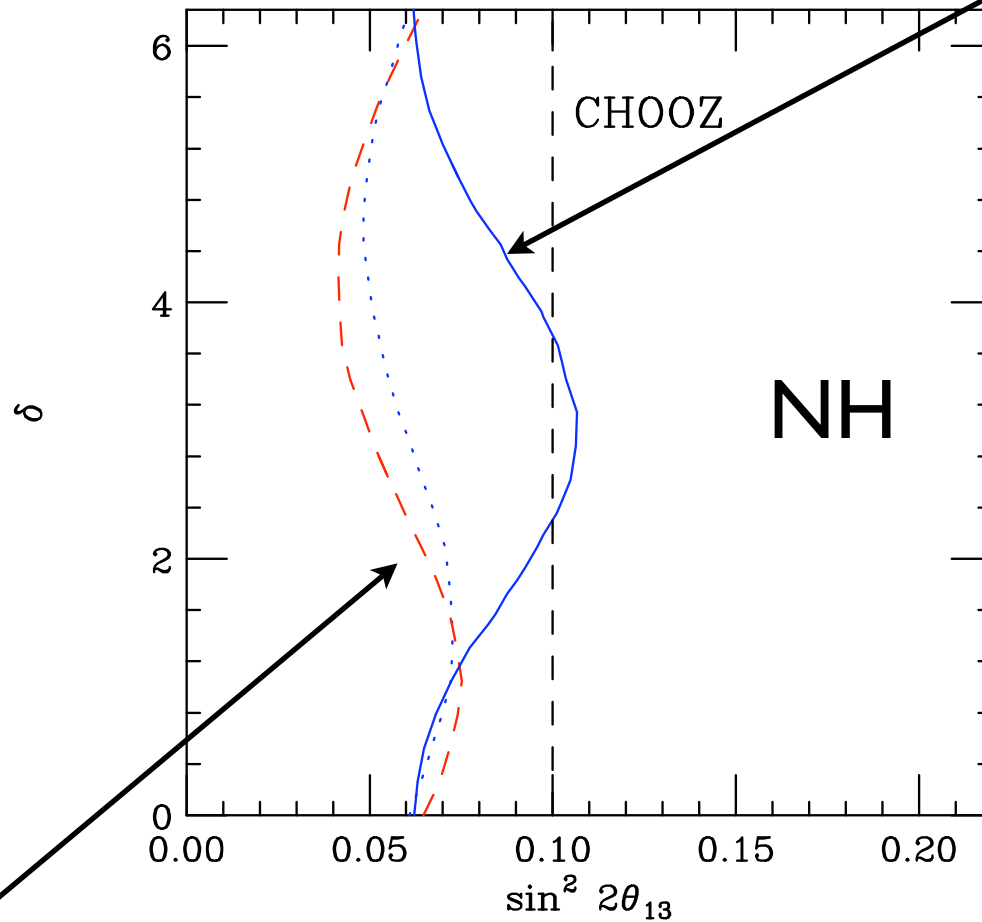
90% at 2 dof  
approx  
97% at 1 dof

2.5 deg & 14 km (b)  $\Delta m_{31}^2 = +3.0 \times 10^{-3} \text{ eV}^2$

2.0 deg & 12 km

# Hierarchy Determination using 2 dof: 90% CL

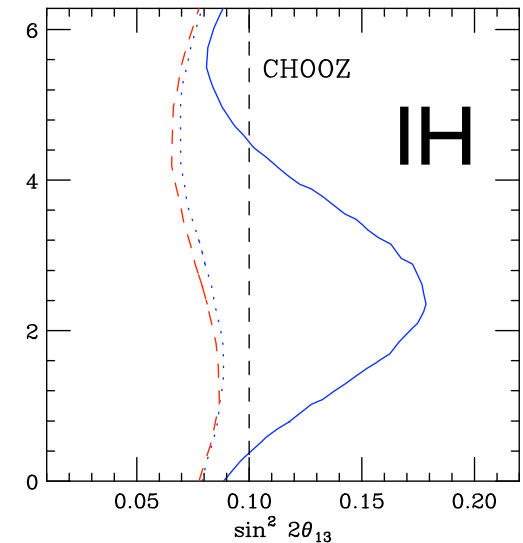
2.5 deg & 12 km



WHY 2 dof ????

90% at 2 dof  
approx  
97% at 1 dof

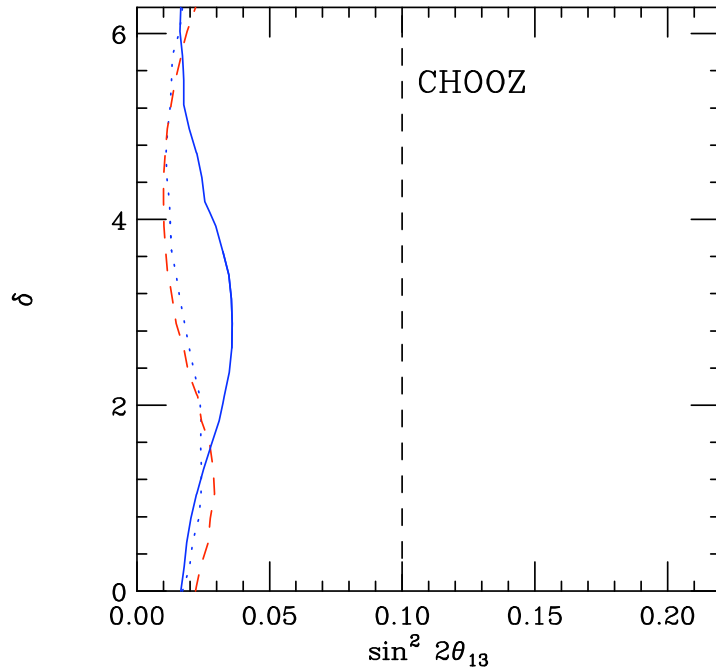
2.5 deg & 14 km (b)  $\Delta m_{31}^2 = +3.0 \times 10^{-3} \text{ eV}^2$   
2.0 deg & 12 km



(b)  $\Delta m_{31}^2 = -3.0 \times 10^{-3} \text{ eV}^2$

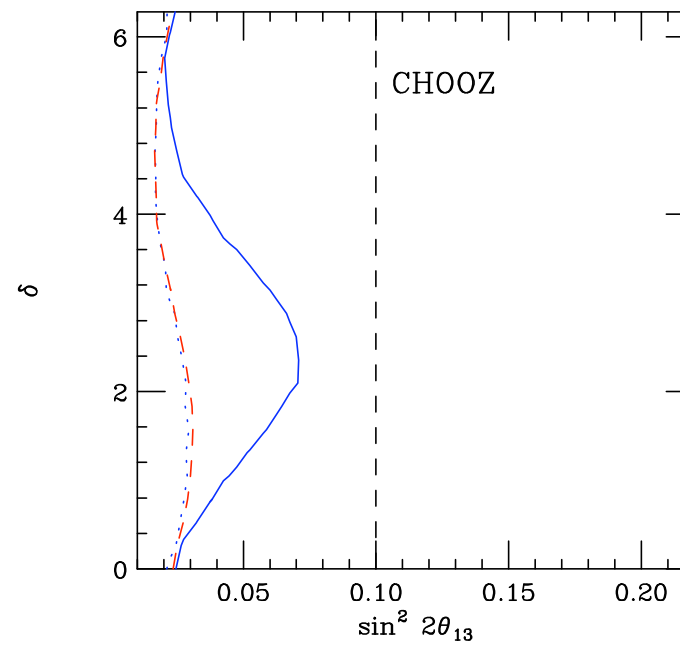
# 5 times Statistics !!!

NH



(b)  $\Delta m_{31}^2 = +3.0 \times 10^{-3} \text{ eV}^2$

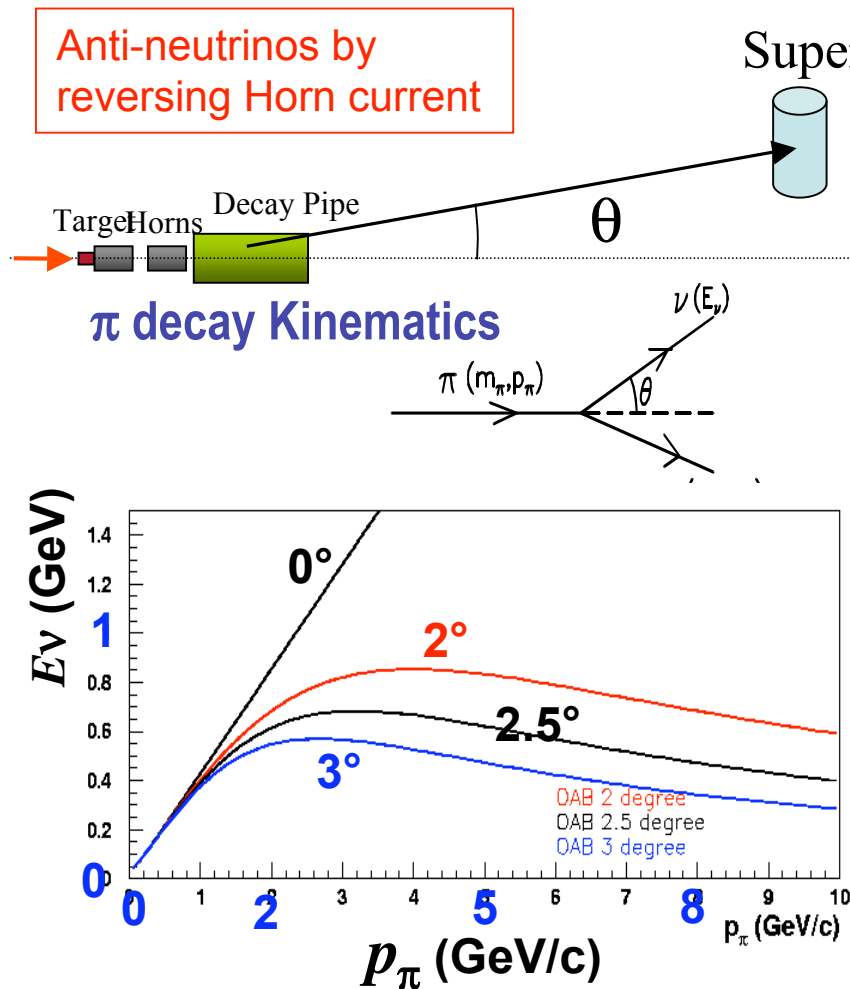
IH



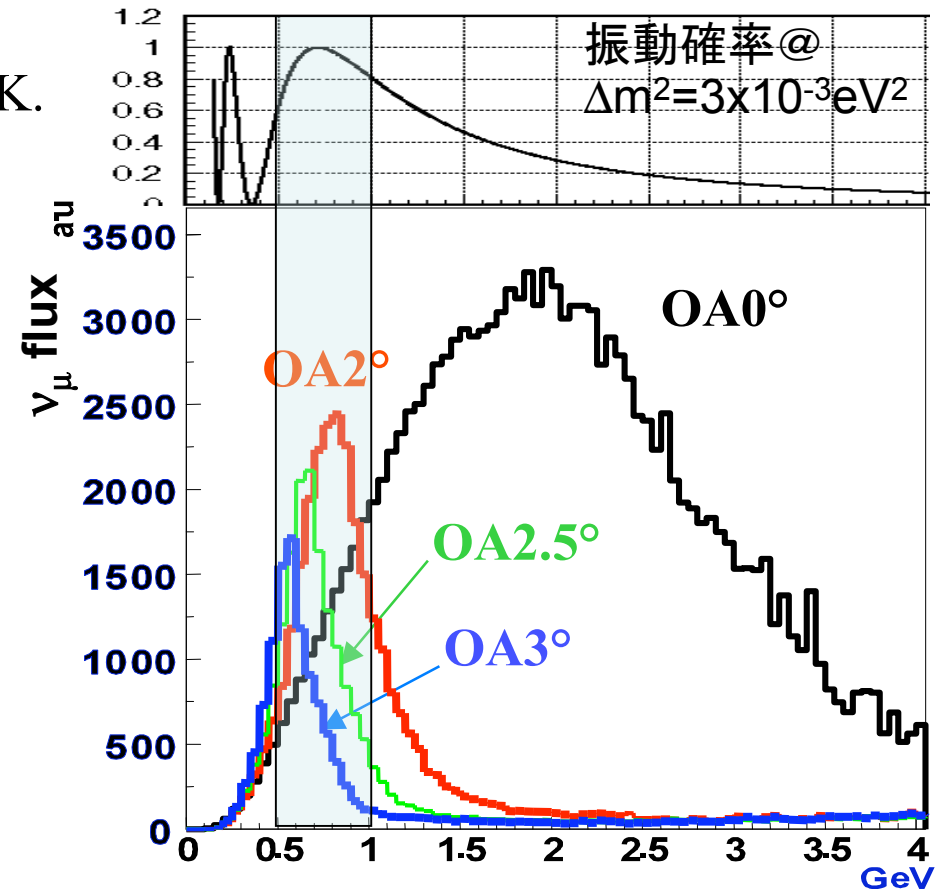
(b)  $\Delta m_{31}^2 = -3.0 \times 10^{-3} \text{ eV}^2$

systematic errors ???

## Narrow intense beam: Off-axis beam



- ◆ Quasi Monochromatic Beam
- ◆ x 2~3 intense than NBB
- ◆ Tuned at oscillation maximum



@SK (OAB 2.5 deg/1 yr, no-osci.)  
 ~ 1030  $\nu_\mu$  CC+NC single rings  
 ~ 970  $\nu_\mu$  CC single rings  
 $\nu_e$  ~0.4% at  $\nu_\mu$  peak

# Suppose T2K ran @ 2.0 deg

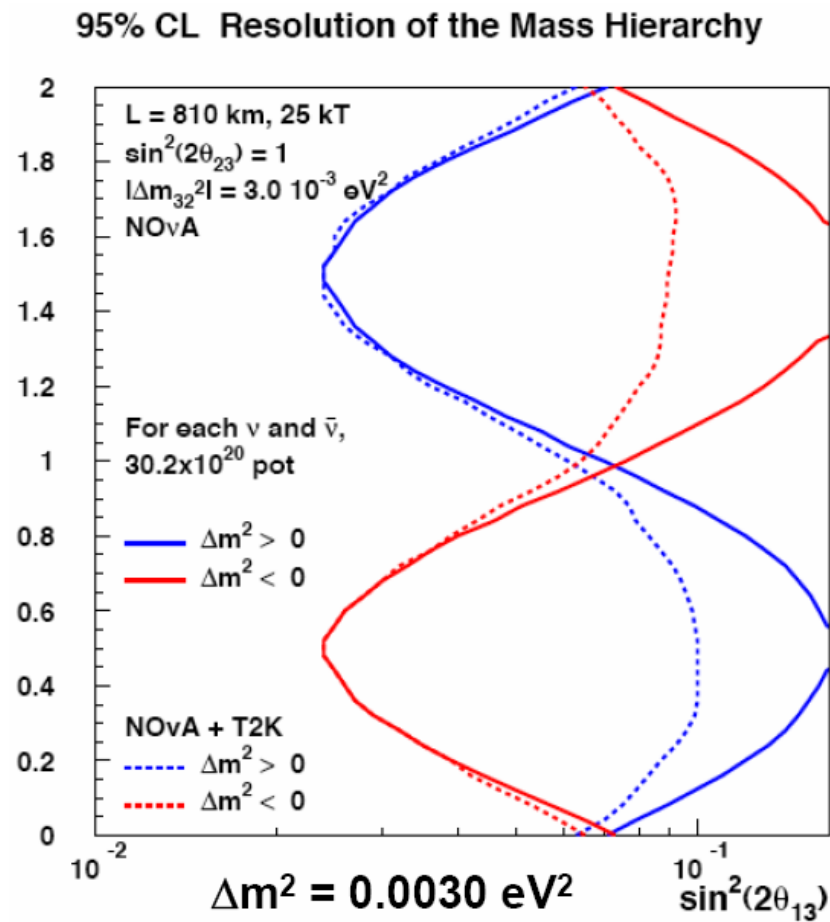
$$\langle E \rangle = 0.75 \text{ MeV}$$

same  $\langle E \rangle / L$  as NOvA 12km

- Increased Statistics:
- Improved sensitivity to  $\sin^2 \theta_{13}$  ???  
(flux, cross section and backgrounds)
- smaller matter effects:

# NOvA + T2K:

## NOvA @ NO-VE 2007



Half Neutrino Running + different  $\langle E \rangle / L$

# Neutrino $\nu$ Anti-Neutrino

## Two Expts. Different L's

T2K

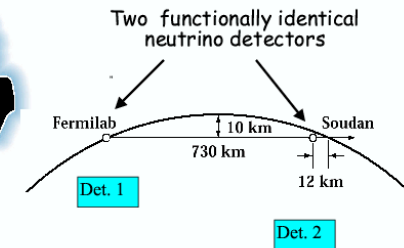
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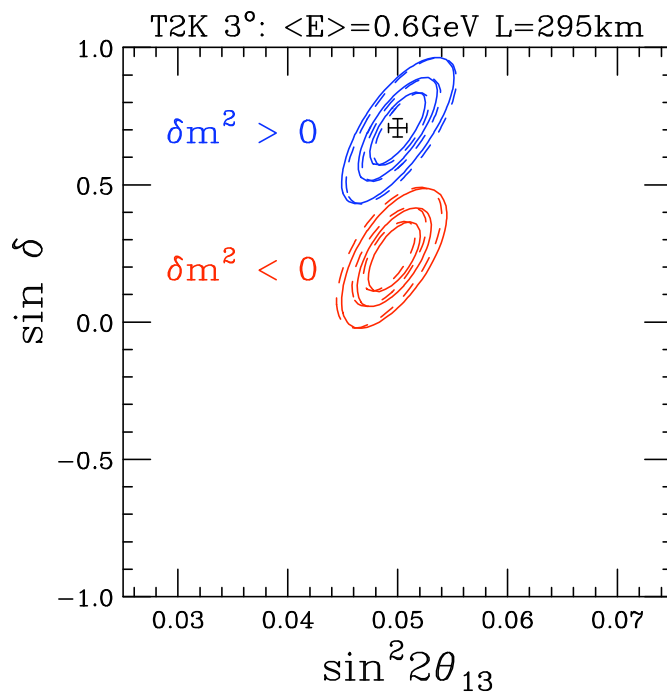
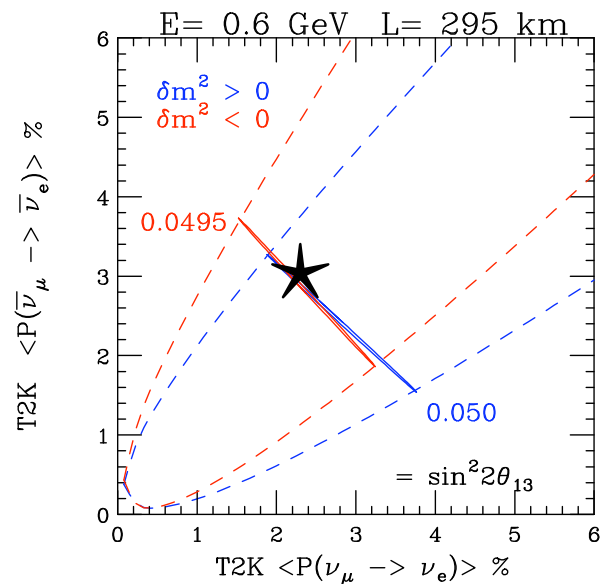
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- ✓ Super-Kamiokande:
  - 22.5 kton fiducial
  - Excellent  $e/\mu$  ID
  - Additional  $\pi^0/e$  ID
- ✓ Hyper-Kamiokande
  - 20 $\times$  fiducial mass of SuperK
- ✓ Matter effects small
- ✓ Study using fully simulated and reconstructed data



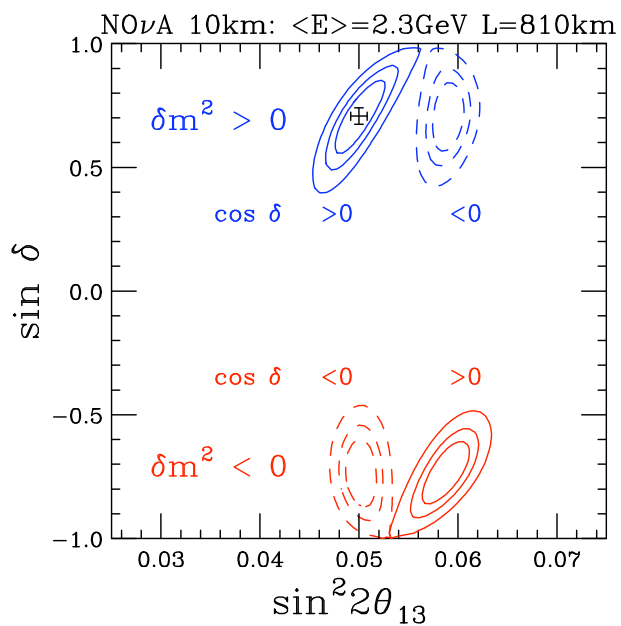
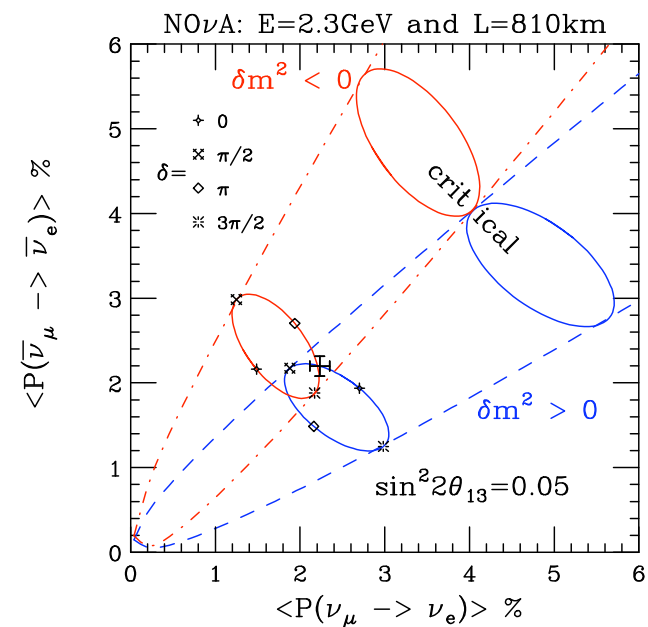
### The NUMI Beamline

NOVA





$$\langle \sin \delta \rangle_+ - \langle \sin \delta \rangle_- \approx 0.47 \sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$



$$\langle \sin \delta \rangle_+ - \langle \sin \delta \rangle_- \approx 1.4 \sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

$$|\langle \sin \delta \rangle_{\text{true}}^{T2K} - \langle \sin \delta \rangle_{\text{true}}^{NO\nu A}| \approx 0$$

$$|\langle \sin \delta \rangle_{\text{fake}}^{T2K} - \langle \sin \delta \rangle_{\text{fake}}^{NO\nu A}| \approx 0.93 \sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

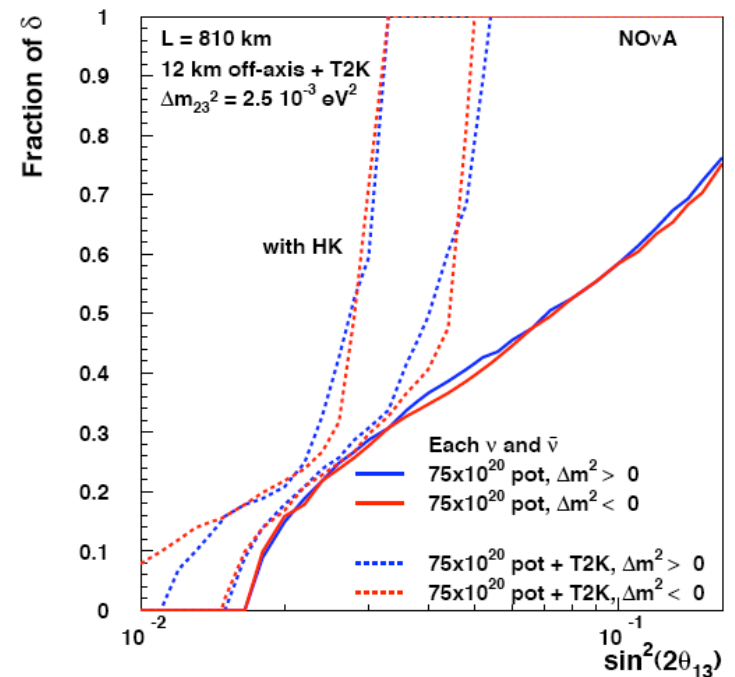
if the measurement uncertainty on  $\sin \delta$   
 $\approx \pm 0.2$

then the two fake solutions are well separated down to

$$\sin^2 2\theta_{13} \approx 0.01$$

Hierarchy is Determined

95% CL



NOνA/PD with T2K Phase 2

# Spectrum Measurements:

- On Axis
- Off Axis - 2nd Peak

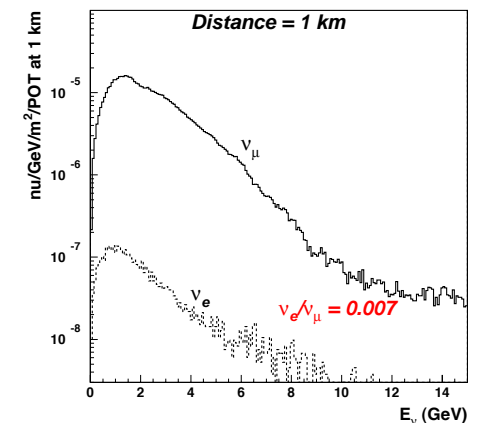
# On Axis Beams:



- 28 GeV protons. 1 MW beam power. Horn focussed
- 500 kT water Cherenkov detector.
- baseline > 2500 km. WIPP, Henderson, Homestake

## Brookhaven Proposal

BNL Wide Band. Proton Energy = 28 GeV

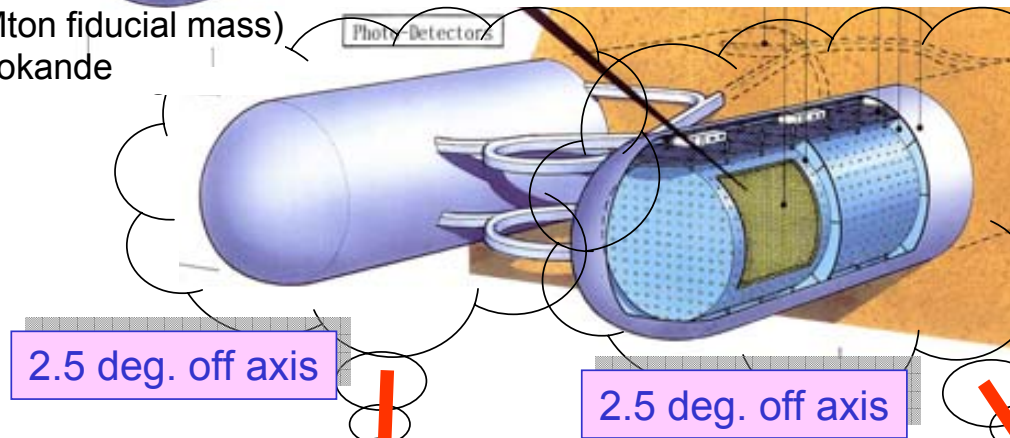


# Off Axis:

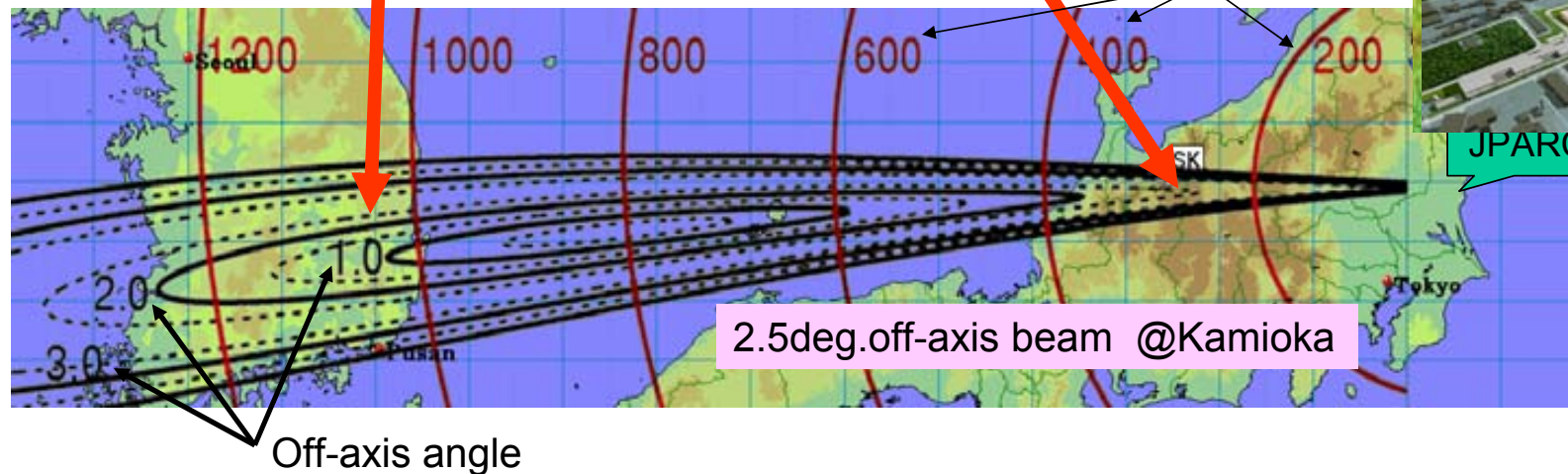


## *Some recent progress: detector in Korea*

1Mton (0.54Mton fiducial mass)  
Hyper-Kamiokande



Total cost must be similar to the baseline design.



see Kajita talk:

# CONCLUSION:

- Determination of Neutrino Hierarchy is Challenging and can effect whether or not the observation of CP violation can be CLAIMED.
- NOvA has a shot, BUT it's VERY  $\delta_{CP}$  DEPENDENT
- T2K + NOvA can substantially reduce the  $\delta_{CP}$  dependence using NEUTRINOS ONLY. IF they run at the SAME  $\langle E \rangle / L$ .
- However, many issues need experimentalist expertise.
- IMHO we need, join task force between T2K + NOvA before this opportunity is LOST FOREVER !!!